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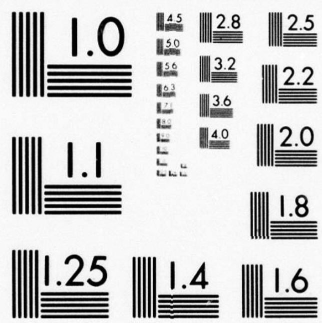
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Volume 2 Final Report

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This final report presents the results of the Demand-Assignment Techniques Study (DATS). The objective of this one-year study is to evaluate demend assignment (DA) techniques for military satellite communications. Demand-assignment provides an effective way to meet growing DOD requirements for satellite communications by enabling many users to share satellite and earth terminal resources. The study is divided into the following four major tasks:

a. Establishment of Selection Criteria
b. Trade-off Investigation of Candidate DA Techniques (over)

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c. Detailed Investigation of Preferred DA Techniques
d. Evaluation of Earth Terminal Reliability and Cost

Results of all study task as well as overall conclusions and recommendations are presented. This volume contains the main body of the report plus technical appendixes.

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Collins report

Volume 2 Final Report

Demand Assignment Techniques Study (DATS) for Military Satellite Communication Applications

Final Report prepared for:
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Section 1

Introduction

1.1 GENERAL

This volume is the Final Report of the Demand Assignment Techniques Study (DATS). The objective of this study is to identify, investigate, and rank candidate demand-assignment (DA) techniques for both SHF and UHF military satellite communication applications. The highest ranked candidates are those demand-assignment techniques that provide an acceptable grade of service to all users in the most cost-effective manner while providing the optimum utilization of the available satellite resources. The complete study is divided into the following four tasks:

Task 1 - Establishment of Selection Criteria.
Task 2 - Trade-off Investigation of Candidate DA Techniques.
Task 3 - Detailed Investigation of Preferred DA Techniques.
Task 4 - Evaluation of Terminal Complexity, Reliability and Cost.

The final report covers the results of all four study tasks.

1.2 NEED FOR DEMAND-ASSIGNMENT

Current and planned Military Satellite Communication Systems can be broadly categorized into UHF and SHF systems in accordance with the user communities they serve. Examples of UHF satellite systems are GAPSAT, FLTSAT, and AFSAT. SHF satellite systems include DSCS I, II, and III, the British SKYNET, and NATO series.

The community requiring UHF communications consists of a large number of low-duty-cycle users that includes a substantial population of mobile users. Their communications requirement is primarily for mutual information transfer among members of one or more nets. Power, weight, size, and cost constraints of these users dictate simple terminals with limited transmitting and receiving capabilities. Such users are presently served best at UHF.

Accommodation of the large UHF military user population in the already overcrowded UHF frequency band will be difficult if users are to be assigned dedicated channels. Furthermore, dedicated assignments will make inefficient use of the limited satellite resources available. Therefore, a demand-assignment concept, where channels are assigned only temporarily to users when they need to communicate and are reassigned to other users when they are idle, will allow better utilization of the satellite resources. With these techniques, communication capability will be provided to a much larger number of users within the limited bandwidth available at UHF.

The SHF frequency band has been used in the past primarily for trunking to support the strategic long-haul communication requirements of the DCS. The high duty cycle and the large volume of traffic involved in trunking requires essentially full-time dedicated links. In the past few years, however, the user community requiring SHF communications has grown considerably. The new SHF users such as FLTOPS and GMF require low-duty-cycle netted communications. The emergence of the new users and their differing communication needs require that SHF SATCOM systems provide both trunking and netting capabilities. Recognition

of this fact necessitates investigation of using demand-assignment techniques at SHF also to provide rapid and responsive service to the low-duty-cycle netted users.

1.3 DEMAND-ASSIGNMENT DEFINITION

Demand-assignment (DA) deals with techniques to provide efficient matching between the time-varying user demands for service and the available system capacity. For a given capacity, a suitably designed DA system can serve a user population substantially larger than that served by fixed assignment of the capacity, provided that the duty cycle of the users is relatively low. Conversely, a fixed-sized user population can be served by a smaller amount of capacity when using a DA system rather than fixed assignment.

Demand-assignment can be divided into two categories and both are considered in this study: demand assignment multiple access (DAMA) and baseband demand assignment (BDA). DAMA refers to matching the available rf satellite capacity to the time-varying user needs. A DAMA system involves a demand-assignment technique and a satellite multiple-access technique. BDA refers to matching the available terminal capacity associated with an rf carrier to the time-varying local user needs. A BDA system involves a DA technique and baseband multiplexing technique. Both DAMA and BDA, either separately or in a hybrid DAMA/BDA form, may be used to achieve maximum utilization of the communication system.

1.4 STUDY BASELINE

The following three major baseline constraints are used to bound the scope of this study:

a. Consider only digital traffic (voice and data).
b. Consider only those terminals that are now in inventory or those that are planned for inventory by the early 1980's.
c. Consider only operational satellites or near-term programmed satellites.

Table 1-1 lists the satellites that are considered by this study. An additional limitation is that the use of demand-assignment has been considered for the general-purpose user only. This study has not treated SIOP, INTEL relay, or WWMCSS users.

Table 1-1. Satellites Considered.

UHF	SHF
FLTSAT GAPSAT	DSCS II

1.5 DEMAND-ASSIGNMENT USERS

Determination of the best DA systems is dependent on the offered user traffic and the available user equipment. Therefore, before demand-assignment systems can be evaluated to determine the optimum choice, the users must be identified and carefully described. Information concerning each user's terminal equipment and traffic must be compiled. From this information a model is constructed for each user, which contains the data required to evaluate the DA candidate. Table 1-2 lists the demand-assignment users that are modeled in this report and also lists the source of traffic statistics used in each model.

1.6 REPORT ORGANIZATION

The DATS final report is divided into eight major sections and three appendixes. Section 2 develops the Evaluation Criteria, which are to be used to rank and compare the DA candidate techniques quantitatively. Section 3 presents the definition of the candidate DA techniques.

Section 4.0 presents the user models and a development of required user model content. In addition it gives a brief description of each user model for both SHF and UHF and gives a node-by-node listing of user traffic. Section 5.0 contains technical background information used in later sections, while sections 6.0 and 7.0 present the evaluation, selection and description of the preferred candidate DA systems for SHF and UHF MILSATCOM systems respectively, based on satellite channel capacity, frequency management and cost considerations. The report is summarized in section 8.0. The following topics are included in the appendices: Voice Traffic Analysis, Data Traffic Analsysis, and SHF System Design and Costing.

1.7 References

1. John D. Bridwell, et al, "A Preliminary Design of a TDMA System for FLEETSAT," ESD-TR-75-137, 12 March 1975.
2. Integrated Tactical Communications System (INTACS) Communications Support Requirements (COMSR) Data Base (A tool for analyzing, designing, and developing communication hardware used by the Department of the Army).
3. Communications Satellite Corporation, "Study of Functional Requirements for Demand Assignment SHF TDMA Modems," Interim Report, 24 May 1975.
4. Arthur D. Little, Inc., "Study of Strategic Communications in the European Missions Area," ADL 09159, C13, 1974.

2.1 PURPOSE

In order to evaluate, rank, and select candidate demand-assignment (DA) techniques, meaningful evaluation criteria by which the candidates can be compared are required. One of the tasks of this study is to establish the criteria to be used in this comparison. The results of the candidate comparison are dependent upon the evaluation criteria utilized. Hence, the criteria must be chosen carefully, and should include channel capacity, frequency-management, and cost considerations, since these factors are of prime importance in selecting demand-assignment candidates for application to military satellite communication systems.

The utilization efficiency of communications capacity when employing fixed assignment is generally low when the capacity is applied to serving a number of small-volume, low-duty-cycle users. This is because each user does not fully utilize the capacity assigned to it but, rather, transmits and receives information during only a fractional part of a diurnal period. Thus, the amount of power times bandwidth product assigned to the user on a fixed basis is generally in excess of the amount needed to handle the actual communications volume for the user. As a result, the number of satellite channels provided and assigned is excessive and wasteful. In contrast, the purpose of demand-assignment augmentation to the communications capability is to maximize the traffic served, per unit of resource utilized.

2.2 EVALUATION CRITERIA CONSIDERATIONS

In order to develop a realistic evaluation criterion function for the demand-assignment subsystem, we must consider the overall communication system of which it is a part. A basic premise is that the performance of the communication system can be improved or the cost of operation of the communication system can be reduced by use of a demand-assignment subsystem.

Ideally, the desirable criterion is the system payoff measured in dollars and defined as the difference between the value and the cost of the communication system, or

$$\text{Payoff} = \text{value} - \text{cost}. \tag{2-1}$$

The communication system cost is a function primarily of the total communication system being evaluated while the value is a function of both the system and the user being served. Clearly, the optimum demand-assignment subsystem is that which maximizes the communication-system payoff. However, since it is virtually impossible to determine the value and the cost of a satellite communication system in a study of this scope, no attempt is made to determine the <u>system</u> payoff for a demand-assignment-augmented communication system. The problem, then, reduces to determining the payoff for the demand-assignment augmentation only. That is, the value and the cost to be determined are those that are added by the augmentation of the communication system by means of a demand-assignment capability.

The payoff of demand-assignment systems is that they make possible the serving of the user requirements with a smaller amount of power and bandwidth resource expenditure than do

fixed-assignment schemes. The amount of payoff is a function of the demand-assignment technique and the parameters of the user model. Since the value depends upon the users being served and varies subjectively from one application to another, the value of the communications capacity is difficult, if not impossible, to determine. Therefore, evaluation criteria applied in this study are based upon more easily definable parameters and the payoff function is excluded from the criteria.

A meaningful guideline for designing demand-assignment candidates is to minimize the communication resource expenditure required to satisfy user-community traffic needs while also minimizing the life-cycle cost. Therefore, the evaluation of DA candidates in this study is based upon expected satellite channel capacity requirements, spectrum availability considerations, and estimated equipment costs.

2.3 EVALUATION CRITERIA DESCRIPTION

The three evaluation criteria utilized in this study are as follows:

S, the number of satellite channels required to serve the traffic
F, the fraction of frequency assignments which must be available
C, the cost of the demand assignment equipment

The bases for these criteria are described in the following paragraphs.

2.3.1 Satellite Capacity Requirements

There are two possible approaches for determining the maximum busy-hour traffic capacity per unit of resource in a demand-assigned communication network. The first approach maximizes the number of terminals or users (with specified traffic requirements) which can be served by the implementation of the demand-assignment system, given a fixed capability of earth and satellite terminals. The second approach minimizes the required capacity in terms of satellite channels, given a fixed number of users. Either approach implies a maximization of busy-hour traffic capacity (for specified user-traffic statistics) provided by the demand-assignment system per unit of ideal channel capacity, that is, per unit of power and bandwidth resources utilized. In this study, the <u>second</u> approach is followed since it is consistent with the objective of determining which candidates satisfy the user-traffic needs with the minimum amount of resources.

2.3.1.1 Satellite Channels Required, S

The primary criterion used in selecting the initial list of preferred candidates is S, the number of power-basis satellite channels required to serve the user-model traffic when utilizing a DA system. For voice applications, S is expressed in equivalent voice-channel quantities, and for data applications, S is expressed as a transmission rate per quantity of bandwidth.

An intermediate measure to be determined for each user model is R, the nominal busy-hour traffic intensity that the DA candidate will handle with a specified fidelity and a specified grade of service. The fidelity and grade of service considered in this study are expressed for two types of traffic as follows. For store-and-forward traffic, the bit error rate must be less than a specified maximum, and the mean message waiting time must be less than a specified maximum. For switched-circuit voice traffic, the audio signal-to-noise ratio must be above a specified minimum, and the number of message overlaps must be less than the blocking probability.

Each DA candidate's nominal busy-hour traffic capacity, R, may be calculated so that S, the number of satellite channels required to handle the traffic, can be determined. Further discussion of the properties of R for the two types of traffic considered in this study is given next.

2.3.1.2 Nominal Busy-Hour Traffic Capacity, R

2.3.1.2.1 R for Store-and-Forward Traffic

For store-and-forward traffic, the nominal busy-hour traffic capacity for the communication system, R, is defined as the maximum traffic the system will handle in bits per second while maintaining a specified bit error rate, BER, and a specified mean waiting time, W. For an ideal, constantly loaded communication channel, the nominal traffic capacity is equal to the bit transmission rate for the channel. W is the mean time duration from submission of the last bit of a message at the transmitting terminal until the reception of the last bit of the message at the receiving terminal. It does not include the time required to enter the message into the transmitting message buffer nor the time required to deliver the message from the receiving message buffer, but it does include waiting time in queue, transmission time, and propagation delay.

The maximum bit transmission rate that a channel can support is limited by the channel bandwidth, the overall link carrier-to-noise-density ratio (C/N_o), the allowable bit error rate, and the modulation technique used. An allowable bit error rate value of 10^{-5} is assumed for the purpose of this study. For coherent binary phase-shift keying (BPSK) modulation, a theoretical energy per bit to noise density ratio, E_b/N_o, of 9.6 dB is required to achieve a bit error rate of 10^{-5}. A 1-dB implementation loss is assumed, so that the required E_b/N_o is 10.6 dB. The bit rate that a single channel will support is

$$r = (C/N_o)/(E_b/N_o) \text{ b/s.} \tag{2-2}$$

In practice, messages will arrive at different terminals at random times so that in some cases there may be periods when messages arrive faster than they can be serviced or transmitted by the channel, while at other times there may be no traffic to transmit. The mean busy-hour traffic rate offered must be low, relative to the capacity, so that the specified mean waiting time is not exceeded.

Initial trade studies are made on the basis of the maximum allowable mean message delay, W. The delay for each of the precedence levels is checked in the detailed studies of the primary candidate systems.

2.3.1.2.2 R for Switched-Circuit Traffic

For switched-circuit traffic, the nominal busy-hour traffic capacity, R, for the communication system is defined as the maximum calling rate in calls per second that the system can accommodate with a specified transmission quality without exceeding the specified blocking probability, B. The communication is transmitted in a digital form. An allowable bit error rate value of 10^{-3} is generally acceptable for digitized voice, resulting in a required E_b/N_o value of 8.0 dB for coherent BPSK modulation.

2.3.2 Frequency-Management Considerations

2.3.2.1 Spectrum Sharing Requirements

The magnitude of the spectrum congestion problem can be appreciated when it is realized that, within CONUS and elsewhere, significant multiple assignment and use of the spectrum

exists. In particular, there are about 10,000 UHF assignments in the US and its possessions for channels, most of which are spaced at 100-kHz increments. Assuming that these assignments are uniformly distributed among approximately 1,682 (0.1-MHz spacing) channels in 168.2 MHz of spectrum between 225 and 328.6 MHz and between 335.4 and 400 MHz, the UHF frequency channel reuse factor is 6. At SHF, there are about 5,000 assignments for channels spaced at typically 20-MHz increments. Assuming that these assignments are uniformly distributed among approximately 50 (20-MHz spacing) channels in 1 GHz of spectrum between 7.25 and 7.75 GHz and between 7.9 and 8.4 GHz, the SHF frequency channel reuse factor is 100. If the interference area is assumed to be limited to a line-of-sight radius of about 15 miles, then the average probability of an SHF assignment being in use in a specific locale is about 5 percent. The occurrence of over-the-horizon interference is also probable a significant fraction of time.

Reuse of frequencies throughout a geographic region is an important concept in efficient utilization of the valuable radio-frequency spectrum. However, reuse significantly increases the probability of interference between terrestrial systems and satellite communication systems (Long, reference 1). In considering frequency sharing between fixed satellite service and terrestrial radio services, there are four conditions that must be satisfied (ITU, reference 2):

a. The signals from the satellite must not cause unacceptable interference to the receivers of the terrestrial service.
b. The signals from satellite earth stations must not cause unacceptable interference to the receivers of the terrestrial service.
c. The signals from terrestrial stations must not cause unacceptable interference to the receivers of satellite-system earth stations.
d. The signals from terrestrial stations must not cause unacceptable interference in the satellite receivers.

These conditions are given in order of priority from the veiwpoint of the terrestrial service already occupying a particular frequency band having a substantial investment in equipment and service. When a proposal is made to allocate the band to a space service on a co-equal basis, it must be demonstrated that the space service will not cause "unacceptable interference" to the terrestrial service or services concerned.

2.3.2.1.1 Satellite-to-Terrestrial-Station Interference

One consideration is the possible interference from the SHF satellite-to-terrestrial microwave line-of-sight (LOS) stations. The CCIR allowable limit for satellite emission flux density, Φ, at the earth's surface in the 7/8-GHz down-link bands is specified (ITU, reference 3) as follows:

> $\Phi = -152$ dB W/m^2 in any 4-kHz band for angles of arrival between 0 and 5 degrees above the horizontal plane, and varying with angle up to $\Phi = -142$ dB W/m^2 in any 4-kHz band for angles of arrival between 25 and 90 degrees above the horizontal plane, under assumed free-space propagation conditions.

The EIRP per transponder of a DSCS II SHF satellite (Pritchard, reference 4) is 28-dB W using the earth coverage antenna. To meet the flux density restrictions, the minimum uniform-energy density bandwidth, w, of the satellite emission at 28 dB W EIRP is 0.2 MHz. The narrow-beam antenna with EIRP of 43-dB W requires $w \geq 6.4$ MHz. In view of the capacity required to meet SHF user needs, it is almost certain that these minimum signal-occupied bandwidths will be substantially exceeded by any practical modulation and multiple-access techniques combination utilized in a demand-assignment communication network. Thus, it is

concluded that interference from the satellite-to-terrestrial LOS systems is not a likely occurrence.

2.3.2.1.2 Satellite-Earth-Station-to-Terrestrial-Station Interference

Within the coordination area of a satellite earth station (Adams, reference 5; ITU, reference 6) it is necessary to check the use of frequencies that are assigned to terrestrial (LOS) stations in the vicinity. In a specific locale certain frequencies must not be used, leaving a subset of the total band which is potentially assignable to the satellite earth station. The fact that a portion of the spectrum is not usable within the coordination area of another station because of terrestrial system use (or other restriction) does not necessarily prohibit its use at the station under consideration. However, reuse of the same portion of the spectrum within the network (except through time-orthogonal or quasi-orthogonal multiple-access techniques) is precluded by the use of a common satellite repeater.

2.3.2.1.3 Terrestrial-Station-to-Earth-Station Interference

A down-link frequency is related to the associated up-link frequency by a fixed amount of frequency offset for a given satellite frequency translation plan. Any frequency within the allocated band may be used for transmission from the satellite, provided that the power is distributed over a sufficiently broad bandwidth. Because of terrestrial transmitters within the receive coordination area of the earth station, the signal-to-interference ratio may not be sufficient on all channels to support the required transmission rate. Thus, it may be necessary to utilize only protected down-link frequency assignments at earth stations, a condition which further reduces the probability of obtaining the required number of assignments.

2.3.2.1.4 Terrestrial-Station-to-Satellite Interference

The probability of this type of unintentional interference is considered negligible, due to restrictions on the EIRP and restrictions on pointing of terrestrial station antennas toward the geostationary orbit (ITU, reference 3).

2.3.2.2 Multiple-Access Considerations

The following multiple-access techniques (Jain, reference 7) are considered in this study:

a. FDMA

Frequency division multiple-access technique in which channels are defined by multiple, separated carrier frequencies with associated channels, thus establishing orthogonal channels.

b. TDMA

Time division multiple-access technique in which channels are defined by multiple, repetitive sets of time slots with fixed start and stop times relative to a frame-synchronization reference. Time-sequential sharing of a common bandwidth permits establishing orthogonal channels.

c. CDMA

Code division multiple-access technique in which channels are defined by unique sets of pseudorandom address codes in the time-frequency domain. Receiver processing is

employed to detect a wanted signal in the presence of others by means of the characteristic quasi-orthogonal code matching. Some immunity or resistance to interference is achieved by means of the receiving process.

The amount of bandwidth required by each multiple-access technique to provide the necessary capacity is fundamental to the frequency-management considerations. For a fixed transponder power level, error rate specification, modulation technique, and user parameters, the several MA techniques require varying amounts and configurations of bandwidth to provide the nominal capacity. For example, when nonuniform frequency spacing (to reduce interference due to intermodulation products generated in a nonlinear repeater) is employed, the FDMA bandwidth utilization efficiency decreases with increasing number of accesses. Similarly, the CDMA bandwidth efficiency is relatively low, even for a small number of accesses, and it decreases somewhat with increasing accesses. For typical values of design parameters, the bandwidth utilization efficiencies for 12 accesses utilizing TDMA, FDMA, and CDMA are 0.85, 0.10, and 0.03, respectively. Thus, while the contiguous bandwidth requirement is high for TDMA compared to that for FDMA, the total spanned bandwidth requirement is less when FDMA intermodulation products are to be avoided. CDMA requires a large amount of contiguous bandwidth and exhibits poor bandwidth utilization efficiency, making it especially difficult to implement from frequency management considerations alone. A quantity termed "interference potential," which considers both bandwidth and peak power levels for multiple access techniques, has been determined previously by Long (reference 1) and leads to similar conclusions. The wider the required bandwidth, in terms of number of spectrum increments, the lower the probability of obtaining the required frequency assignments.

However, the FDMA efficiency is not likely to be as low as suggested, since nonuniform spacing to avoid intermodulation is not likely to be employed. The efficiency is more likely determined mostly by losses due to guard bands (interchannel spacing) and typically will have a value of 0.8 to 0.9. The employment of uniform spacing requires adequate power-amplifier "back-off" to reduce intermodulation products to an acceptable level. It is assumed here that the DSCS repeaters are operated in a linear mode.

2.3.2.3 Frequency-Assignment-Availability Requirement, F

The frequency-management considerations used in evaluating the DA candidates are embodied in a criterion, F, defined by

> F = The fraction of the frequency assignments comprising a specified bandwidth which must be available for assignment (in an earth terminal locale), such that the probability of obtaining the number of assignments needed by the DA candidate to serve the user model traffic is 0.5.

It is assumed here that an assignment in the appropriate allocation can be obtained for MILSATCOM use in a locale if it is not in use by a terrestrial system; that is, it is available for use. This factor is computed only for the simplified case of uniform traffic levels at all earth terminals and uniform probability of obtaining any assignment at any terminal. These assumptions make tractable the calculation of F for the DA candidates applied to the user models with an accuracy commensurate with the knowledge of terrestrial-system spectrum usage.

2.3.3 Demand-Assignment System Equipment Cost, C

Ideally, the cost evaluation criterion to be calculated for the DA candidates applied to the user models is the life-cycle cost. However, in this study it has been deemed expedient and adequate for ranking of candidates to estimate the DA system equipment production costs only.

These production costs include all parts of the DA system (demand-assignment processor, modulator/demodulator, mux units, etc) which would be added to the existing terminal equipment. However, the cost of already existing terminal equipment, which may need modification because of the addition of DA, has not been included.

2.4 EVALUATION CRITERIA APPLICATION FOR SYSTEM EVALUATION

The overall system models for the baseline candidate systems must be evaluated in terms of the evaluation criteria. For a major portion of the study, only one criterion is used, the required number of satellite channels, S. There is need to pare the list of candidate systems under evaluation to a manageable number. This is done by applying common-sense engineering judgments to eliminate some of the less-favorable-performance candidates from consideration after documentation of the reasons for removal. The methodology of computing the evaluation criteria values for the DA candidates applied to the user models is outlined in the following paragraphs.

2.4.1 Satellite Channels Required, S

The initial preferred candidate DA techniques are identified by determining for each the nominal busy-hour traffic capacity, R, per satellite channel. This is indicative of the number of satellite channels required to serve the offered user model traffic. For voice traffic, the number of channels required by the DA candidates as a function of the incoming traffic intensity per terminal is analyzed in appendix A. The results are shown in section 5 and applied to the specific SHF user model requirements in section 6. For data traffic, the number of terminals served by the DA candidates as a function of the fraction of satellite channel capacity used by a single terminal is analyzed in appendix B. The results are shown in section 5 and applied to the specific UHF user model requirements in section 7.

2.4.2 Frequency-Assignment-Availability Requirement, F

As defined in paragraph 2.3.2.3, the frequency-management evaluation criterion is:

F = fraction of assignments that must be available so that the probability of obtaining the number of assignments needed to serve the traffic is 0.5.

This criterion's purpose is to coarsely indicate the degree of terrestrial-system spectrum usage that can be tolerated by the demand assignment candidate with a 50-percent probability of success when serving the user model traffic.

The probability of obtaining the number of assignments required to handle a specified amount of traffic for each DA candidate as a function of the fraction of assignments available is developed in this section. This relationship is used to determine the allowable fraction of assignments in use so that the probability of obtaining the required number is 0.5. Expressions are derived for DAMA-TDMA, DAMA-FDMA, BDA-FDMA, and BDA-TASI-FDMA candidates. The analysis tools are utilized in section 6 for SHF user models and in section 7 for UHF user models. This development is based in part on previous results presented by Long (reference 1).

2.4.2.1 Notation

a = number of earth terminals in the network, each assumed to have identical traffic statistics and identical assignment environments.

k = number of assignments required for providing a specific amount of network traffic-handling capacity, for the DA candidate.

m = total number of specified-bandwidth assignments in the transponder bandwidth under consideration. This value applies to both uplinks and downlinks, alike.

n = number of assignments which can be obtained for application to the user model traffic. For simplicity in analysis it is assumed that the n for uplinks is the same value as n for downlinks and that the value is identical at all terminals.

q = (1 - n/m) = fraction of assignments "in-use" by terrestrial systems at each terminal locale. This assumes that any assignment not in use can be obtained for MILSATCOM use.

$p = (1 - q) = \frac{n}{m}$ = probability of one transmit assignment being obtainable at one earth terminal.

$p^2 = (\frac{n}{m})^2$ = probability of one transmit and one receive assignment being obtainable at the respective terminals of one end-to-end link.

p^{ak} = probability of a given k transmit assignments being available at all a earth terminals.

$(p^2)^{ak} = p^{2ak}$ = probability of a given k transmit and receive assignments being available at all a earth terminals.

2.4.2.2 TDMA Candidates

With wide-band TDMA, all terminals must transmit at the same high bit rate and thus require the same number of transmit assignments, regardless of the amount of traffic offered per terminal. Thus, from frequency-management considerations, there is no advantage to employing BDA-TDMA in a typical spectrum-use environment.

For wide-band DAMA-TDMA, the k assignments must be contiguous. The number of non-overlapping integral assignment subsets of size k in a total of m assignments is [m/k], where [ ] indicates the integer value of the quantity. This is a lower bound on the number of independent k subsets. The number of subsets, allowing overlapping, is (m-k+1), an upper bound on the number of independent subsets. Considering all m possible assignments and based on the assumption of independence among subsets, the probability of k contiguous assignments not being obtainable at all earth terminals is:

$$\left.\begin{array}{ll} q_k = (1 - p^{ak})^{[m/k]}, & \text{lower bound} \\ q_k = (1 - p^{ak})^{(m-k+1)}, & \text{upper bound} \end{array}\right\} \text{for transmit assignment only} \qquad (2\text{-}3)$$

$$\left.\begin{array}{ll} q_k = (1 - p^{2ak})^{[m/k]}, & \text{lower bound} \\ q_k = (1 - p^{2ak})^{(m-k+1)}, & \text{upper bound} \end{array}\right\} \text{for transmit and receive assignment} \qquad (2\text{-}4)$$

The probability of obtaining <u>at least</u> one k-member assignment subset is $P = 1 - q_k$, for each of the above cases.

For comparisons with other DA systems, the value of q which results in a specific value of P, say P = 0.5, is computed. The equations for computing the value of q which yields P = 0.5 are listed in table 2-1. The ratio of the upper bound to the lower bound is typically on the order of 3 or less for the parameter ranges of interest. Rather than presenting both bounds in the results sections, only the geometric mean is computed and presented.

Table 2-1. Equations for q, the Allowable Fraction of Assignments in Use by (Terrestrial) Systems (For a 50% Probability of Obtaining Required Assignments).

DA CANDIDATE	TX AND RX ASSIGNMENT	TX ONLY ASSIGNMENT
DAMA-TDMA, BDA-TDMA, and BDA-TASI-TDMA	$q = (q_\ell \cdot q_u)^{1/2}$, where $q_\ell = 1 - \left\{1 - .5^{1/[m/k]}\right\}^{1/(2\,ak)}$ $q_u = 1 - \left\{1 - .5^{1/(m-k+1)}\right\}^{1/(2\,ak)}$	$q = (q_\ell \cdot q_u)^{1/2}$, where $q_\ell = 1 - \left\{1 - .5^{1/[m/k]}\right\}^{1/(ak)}$ $q_u = 1 - \left\{1 - .5^{1/(m-k+1)}\right\}^{1/(ak)}$
DAMA-FDMA	$q = 1 - p_1^{1/(2\,a)}$	$q = 1 - p_1^{1/a}$
*BDA-FDMA	$q = 1 - p_1^{1/a}$	$q = 1 - p_1$
*BDA-TASI-FDMA	$q = 1 - p_1^{1/a}$	$q = 1 - p_1$

*Since the baseband multiplex technique has no effect on q, the equations are applicable to both FDM- and TDM-multiplex candidates.

2.4.2.3 FDMA Candidates

With FDMA through a common repeater, no uplink or downlink frequency may be used by more than one link at a time. Based on previous results (Long, reference 1), the probability of obtaining at least k frequency assignments is

$$P = \sum_{v=k}^{m} \binom{m}{v} (p_1)^v \, (1 - p_1)^{(m-v)} , \qquad (2\text{-}5)$$

where p_1 = probability of obtaining one frequency assignment at the number of earth terminals applicable to the DA candidate under consideration.

Of interest here is the value of p_1 which yields $P = 0.5$, as for the TDMA case. According to an approximation for the binomial distribution (Abramowitz, reference 8), let the summation in equation (2-5) yield a value, $Q(F \mid \nu_1, \nu_2)$, where F is tabulated and where

$\nu_1 = 2(m - k + 1)$,

$\nu_2 = 2(k)$, and

$$p_1 = \frac{k}{k + (m - k + 1)F}$$

According to the reference, for the range of m and k values of interest, $F \simeq 1$ for $Q = 0.5$. Therefore,

$$p_1 \simeq k/(m + 1) , \qquad (2\text{-}6)$$

which can be computed for specific traffic levels for the DA candidates.

The probability of obtaining one assignment is $p_1 = p^J$, where J is the required number of joint occurrences of assignments. For each DA candidate system, the value of J is a function of the number of earth terminals at which assignments must be obtained and whether or not receive protection is desired, as listed in table 2-2.

Table 2-2. J, Number of Joint Occurrences for Each Assignment.

DA CANDIDATE	TX AND RX ASSIGNMENT	TX ONLY ASSIGNMENT
DAMA-FDMA	$2 \cdot a$	a
BDA-FDMA	a	1
BDA-TASI-FDMA	a	1

The difference in J values for DAMA and BDA is that with BDA a transmit assignment is needed only at the one earth terminal utilizing the rf channel, whereas with DAMA the channel is utilized by any of the earth terminals on demand and hence assignment is required at all $\underline{a}$ terminals. For receive protection, assignments are required at all $\underline{a}$ terminals for both BDA and DAMA in a fully connected network.

Values of both p_1 and J are determined by system parameters, so that $q = 1 - p_1^{(1/J)}$ may be calculated for each candidate. The equations are listed in table 2-1.

2.4.2.4 CDMA Candidates

The expression for the probability of obtaining the assignments required for CDMA is similar to that for TDMA. However, the number of simultaneous, contiguous assignments required is approximately $b \cdot k$ rather than k, where b is the desired signal-to-self-interference ratio, typically ≥ 10. Hence, the probability of obtaining the assignments required for CDMA is significantly less than for TDMA, and CDMA systems are not considered in detail in this study.

2.4.2.5 Application

The methodology employed is as follows:

a. Specify a transponder bandwidth to be considered.
b. Specify the frequency-assignment bandwidth to be considered. The ratio of the two bandwidths determines the value of m.
c. Iteratively select a value of k, the required number of assignments. This determines S, the number of satellite channels to be available.
d. Determine the traffic that can be served by each DA candidate, given S, using the DA performance curves of section 5.
e. Compute $p_1 = k/(m + 1)$.
f. Compute q using the appropriate equation from table 2-1.
g. Graphically present the amount of traffic served as a function of q for each candidate for the parameters specified.

The application of the frequency management considerations in the evaluation of DA candidates is conducted in sections 6 and 7.

2.4.3 DA System Equipment Cost, C

The determination of DA system equipment cost for the evaluation of SHF candidates is performed in appendix C and section 6. The cost evaluation of UHF candidates is performed in section 7. The methodology employed is to present the designs of the highest ranked demand-assignment candidates using the required satellite channels, S, and the required frequency assignment availability, F, by providing a detailed block diagram for each candidate along with an explanation of system operation and unit cost. Thus, the total cost is derived by summing the unit costs for each candidate.

2.5 REFERENCES

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3.1 DEMAND-ASSIGNMENT CONCEPTS

Demand assignment involves techniques to provide equitable matching between time-varying user needs and available system capacity. For a given available capacity, a suitably designed demand-assignment system can serve a user population substantially larger than that served by fixed assignment of the capacity, provided that the duty cycle of the users is relatively low.

Demand assignment in satellite communication networks may be considered in two senses: demand assignment multiple access (DAMA) and baseband demand assignment (BDA). DAMA refers to matching the available rf satellite capacity to the time-varying user needs. A DAMA system involves a demand-assignment technique and a satellite multiple-access technique. BDA refers to matching the available terminal capacity associated with an rf carrier to the time-varying local user needs. A BDA system involves a DA technique and a baseband multiplexing technique. A satellite network may employ DAMA, BDA, or both simultaneously, forming a hybrid BDA/DAMA system.

To be cost-effective, from a satellite utilization viewpoint, the demand-assignment technique must permit a high traffic throughput. From the earth terminal user's viewpoint, an acceptable grade of service should be provided and the equipments associated with the demand-assignment control and protocol should be simple and low cost. From the system viewpoint, a cost-effective demand-assignment technique is one which serves the needs of the maximum number of users with the lowest overall cost. The military system user is also concerned about issues of vulnerability to jamming, flexibility to adapt to rapidly changing conditions, susceptibility to operator malpractice and electromagnetic interference, reliability, availability, and compatibility with terrestrial-link protocols and priority provisions.

3.2 CAPACITY-ASSIGNMENT CATEGORIES

Assignment schemes may be categorized as follows:

a. Fixed assignment: Users have a long-term, exclusive system capacity assignment.
b. Random assignment: Users seize and release capacity at will, with retransmission required when interference due to contention occurs.
c. Polled assignment: Each user waits for an indication that his "turn" in a sequence has arrived. The total capacity is available for his exclusive use either until all stored messages have been transmitted or a specified time interval has elapsed.
d. Reservation assignment: Each user makes a request for reserved, exclusive use of capacity when he has traffic ready for transmission.

The categories are further described in the following paragraphs.

3.2.1 Fixed Assignment

In fixed assignment, a designated amount of system capacity is allotted to a user or terminal on a permanent basis for an extended period. Fixed assignment is clearly most suitable for cases where the traffic accessing the system does not vary with time; that is, the system can

be sized for 100 percent loading by a constant traffic level. The amount of assigned capacity must be carefully matched to the user's traffic level and transmission capabilities.

3.2.2 Random Assignment

Random assignment is a time-sequential, user-contention, capacity-sharing strategy. There is no control channel, per se, but provisions are required for dealing with user contention for the message channel. It is convenient to further classify this category according to the nature of the length of individual transmissions and the degree of coordination of the transmission start times. The individual transmissions can be either fixed or random in length, and the message-transmission start times can be either synchronized or unsynchronized among the several users. The commonly used terminology is given in paragraph 3.4.

3.2.3 Polled Assignment

Polled-assignment schemes utilize an actual or virtual control channel (orderwire) for indicating to the user that its "turn" to transmit messages has arrived. The currently polled user has exclusive use of the capacity until he has transmitted all messages in his queue. Either central or distributed control may be employed.

3.2.4 Reservation Assignment

In a reservation-assignment scheme, contention is resolved before transmission by means of a reservation request system. Thus, a small portion of the total capacity must be dedicated to handling and granting of requests. Various assignment schemes can be utilized to provide user access to the reservation orderwire, that is, the channel capacity designated for use in making requests. Examples are given in paragraph 3.4.

3.3 COMPOSITION OF CAPACITY-ASSIGNMENT SYSTEMS

A capacity-assignment system is composed of several functional entities. In describing a system, it is convenient to specify the purpose or type of the system and the scheme by which each major function is accomplished. Table 3-1 depicts the composition of assignment systems, as considered in this report. Listed are the categories of system types, message-channel assignment schemes, and control-channel schemes from which assignment systems can be constituted.

Table 3-1. Composition of Assignment Systems.

SYSTEM TYPES	MESSAGE-CHANNEL ASSIGNMENT SCHEMES	CONTROL-CHANNEL SCHEMES
Fixed assignment	Preassigned (fixed)	Not required
Demand assignment multiple access (DAMA)	Random Polled Reservation	Fixed Random Polled None

Table 3-1. Composition of Assignment Systems (Cont).

SYSTEM TYPES	MESSAGE-CHANNEL ASSIGNMENT SCHEMES	CONTROL-CHANNEL SCHEMES
Baseband demand assignment (BDA)	Random	Fixed
	Polled	Random
	Reservation	Polled
		None

There are many possible combinations of techniques which produce numerous specific systems. In addition, hybrid systems employing both BDA and DAMA are potentially feasible.

In implementing assignment systems of the types considered here, it is necessary to employ a multiple-access technique for sharing of the rf satellite capacity among "channels" and a multiplexing technique is necessary for sharing of the baseband capacity among users when BDA is used.

Examples of multiple-access techniques utilized in DAMA systems include the following:

a. Frequency division multiple access (FDMA), in which channels are defined by multiple, separated carrier frequencies with associated bandwidths.
b. Time division multiple access (TDMA), in which channels are defined by multiple, repetitive sets of time slots with fixed start and stop times relative to the frame-synchronization reference. The designated users active during an interval share a common bandwidth, but in a time-sequential manner, which permits establishment of orthogonal channels.
c. Code division multiple access (CDMA), in which channels are defined by unique sets of address codes in the time-frequency domain. Receive-processing is employed to detect a wanted signal, in the presence of others, which is distinguished by means of characteristic quasi-orthogonal codes.

Examples of multiplexing techniques utilized in BDA systems include the following:

a. Frequency division multiplexing (FDM), in which channels are defined by separated bandwidths in the frequency domain.
b. Time division multiplexing (TDM), in which channels are defined by distinct, repetitive slots in the time domain.

3.4 PRACTICAL ASSIGNMENT SYSTEMS

The several possible combinations of each message-channel assignment scheme with each control-channel scheme listed in table 3-1 for DAMA and BDA systems have been considered, as a preliminary part of the study. Several have been ruled out from further investigation because the combination of assignment and control schemes is unrealistic or impractical. The remaining (valid) combinations which are considered further are listed in table 3-2. The combinations apply, in principle, to both DAMA and BDA systems, although a particular combination may be more effective for a DAMA application than for BDA, or vice versa. In

addition, fixed assignment of the message-channel capacity is initially evaluated as a candidate for handling data traffic.

Table 3-2. Practical Combinations of Schemes Applicable to BDA and DAMA Systems.

MESSAGE-CHANNEL ASSIGNMENT SCHEME	CONTROL-CHANNEL SCHEME	*COMMENTS
a. Random	None	Examples: pure random, pure ALOHA, slotted ALOHA
b. Polled	Fixed	
c. Reservation	Fixed	Examples: SPADE, UMSTEAD
d. Reservation	Random	Includes TASI for BDA
e. Reservation	Polled	Similar to reservation/ fixed combination
*The systems identified here are described briefly in the text.		

a. In random assignment of message-channel capacity there is no requirement for a control channel. However, there are certain rules which must be defined and followed in the network. For example, a pure random-assignment system is defined as one in which the message-transmission length and the message-transmission start time are each random variables. ALOHA types of random-assignment systems are defined as having the requirement that the message be divided into transmission "packets" of fixed length. When the packet start times are random, the packet-transmission scheme is called pure-ALOHA type (random assignment). When the packet start times are synchronized among users, the scheme is called a slotted-ALOHA type.

b. A polled-assignment system with fixed-assignment control may utilize either an actual or a virtual control channel. In the first case, some of the capacity is devoted to sequentially polling the users in turn to determine if the user being queried has traffic to transmit. If so, the user transmits all traffic which it has in queue. If not, a negative reply is sent (or implied), thus causing the poll to advance to the next user. Central control is inherent to this approach. Because of the relatively long round-trip propagation delay times in satellite links, time required to determine that a user does not have an active need for capacity can result in significant inefficiencies.

   A polled-assignment system with a virtual control channel is similar in operation to the previous case, except that there is no actual control channel. Instead, distributed control is employed, whereby each user listens to all transmissions and waits until it determines that the user which <u>precedes</u> it in the "polling" sequence has completed transmission. This event is the indication to the present user to begin transmission of its queued messages followed by an end-of-transmission indicator.

c. A reservation-assignment system with a fixed-assignment control channel (orderwire) provides exclusive capacity to each user for making requests for (exclusive) message-

transmission capacity. A specific amount of capacity will be reserved for use for that user by the control mechanism. Reservation systems may employ either central or distributed control. In the latter method, each user maintains records of what capacity has been reserved and thus knows the remaining capacity for which it can place a reservation, as required by its traffic load.

The commercial INTELSAT SPADE DAMA system is a single channel per carrier (SCPC) FDMA message channel system in which a separate, fixed-assignment TDMA orderwire channel is provided for each terminal, so that all terminals can copy all orderwire traffic with a single modem. The granting of communications channels is effectively done in parallel by all of the terminals individually rather than by a central control, with each terminal maintaining a list of channels which are available. The military UMSTEAD DAMA system combines the SCPC technology of the SPADE system with current cryptographic technology to provide a secure satellite voice and data network.

d. The reservation-assignment system with a random assignment orderwire is different from the preceding case in that there is contention for the reservation-making capacity. After the user obtains a reservation for message-channel capacity (perhaps after making several attempts, necessary due to contention), it waits until its reserved interval in time arrives.

One example of a reservation-assignment system is time assignment speech interpolation (TASI). This is a BDA, voice-frequency system that exploits the statistically low activity on incoming channels to interpolate speech spurts onto a smaller number of transmission channels. Since full-duplex voice circuits send speech in one direction on one channel and in the reverse direction on another, each channel is idle an average of half the time while users are listening rather than talking. Pauses between words and phrases add to the idle time, so that useful energy is transmitted an average of only 40 percent of the time. The TASI system assigns one talker and the corresponding listener to an available channel and then reassigns the channel to another talker-listener pair, if necessary, when the end of the current talker's speech burst is detected.

e. The reservation/polled combination of schemes employs polling on an orderwire to permit a user to make a request (reservation) for message-channel capacity. Since the orderwire traffic volume is a small fraction of the message traffic volume for most users, there is not much difference in the performance of fixed- and polled-control-channel reservation-assignment systems.

These combinations of message-channel assignment schemes and control-channel schemes are the practical candidates for evaluation in the trade-off investigations of DAMA and BDA systems for military satellite communications. More detailed definitions of systems, with appropriate engineering-option selections, are made when required for further evaluation throughout this study.

The military SATCOM user community can be divided into two parts, those using the UHF frequency band and those using the SHF band. The UHF user can be classified as a large community of low-duty-cycle users requiring netted communications while the SHF user community consists of a mixture of high-volume trunking users as well as low-duty-cycle netted users. The use of demand-assignment, where channels are assigned only temporarily as required, will allow better utilization of the satellite resources available to both frequency bands.

The purpose of the user model is to describe the users of SATCOM resources to the level of detail required to aid in the selection of optimum demand-assignment techniques. The user models were derived from a study of each of the user networks, their data interfaces, message lengths, traffic statistics, communication requirements, existing and planned equipment deployment schedule, etc. This data was compiled into two different categories: equipment models and traffic models. These two models were then combined to form the user models which are applied during evaluation of the candidate DA systems.

4.1 USER MODEL DEVELOPMENT

The user model information is used for the evaluation of candidate DA systems. Each candidate DA system is described mathematically by a particular queuing model or traffic equation. The user model information is then substituted into the appropriate queuing model or traffic equation for numerical evaluation of each candidate DA system. Therefore, determination of what information should be contained in a user model can be accomplished by examining the makeup of the queuing models and traffic equations. As a minimum, each user model should contain all the input variables required by the queuing model or traffic equation. Table 4-1 lists the required user model parameters for both voice traffic and data traffic.

Table 4-1. Required User Model Parameters.

VOICE TRAFFIC	DATA TRAFFIC
Number of terminals (N)	Number of terminals (N)
Mean call rate per terminal (λ')*	Mean call rate per terminal (λ')*
Call rate per coverage area (λ)*	Call rate per coverage area (λ)*
Mean holding time ($\overline{X}$)	Mean message length (ℓ)
Mean traffic intensity per terminal (A')	Maximum waiting time (W_{max})
Traffic intensity per coverage area (A)	Transmission rate
Acceptable blocking probability (B)	
Data rate/channel	

*Primes are used to indicate single terminal parameters, as contrasted with parameters of the total satellite network.

4.2 SHF USER MODEL

The SHF user community requiring demand assignment is composed of Navy Fleet Operations (FLTOPS), the Ground Mobile Forces (GMF) and the Defense Communications System (DCS). These three users present: (1) a wide range of requirements for voice and data traffic, (2) a wide range of terminals from small, mobile terminals to large, fixed terminals, and (3) a wide range of traffic requirements from low-volume, low-duty-cycle traffic to high-volume, high-duty-cycle traffic. The SHF user models are derived by combining the SHF equipment (terminals) models and the SHF traffic models into composite models which completely describe each SHF user. Information used in the models was derived from government documents describing the users; from equipment specifications; from government-compiled data bases; or, in the absence of any of the above, from careful synthesis based upon contractor experience with each user.

4.2.1 SHF Equipment and Link Models

Table 4-2 is a summary of the terminal hardware for the users in each of the three SHF user models. These terminals are currently being used with DSCS II and will also be used with DSCS III when it is launched. In addition, it is anticipated that a new family of lower-cost SHF terminals will emerge for use with DSCS III. However, their rf characteristics are expected to be very similar to those of current terminals and thus are not listed separately in table 4-2. Included in the table are lists of terminal EIRP, G/T, and number of transmit (T) and receive (R) carriers which can be utilized. These parameters, together with the satellite characteristics, are used here to compute the link carrier power to noise power density ratio (C/N_o) and the resultant maximum bit rate for typical users in the user models.

The C/N_o for an up-link or a down-link is computed in decibel form by the equation,

$$(C/N_o)_{dB} = EIRP + (G/T) - (L_p + L_m) + 228.6, \text{ dB}, \tag{4-1}$$

where

EIRP = the transmitting (earth or satellite) terminal equivalent isotropic radiated power on the link, dBW.

G/T = the receiving terminal figure of merit in terms of antenna gain relative to noise temperatures, dB/°K.

L_p = nominal propagation and absorption losses, dB.

L_m = miscellaneous terminal, fading, and rain-induced losses expected a specified fraction of time, dB.

The bandwidth requirement for data transmission using quaternary phase-shft keying (QPSK) modulation including guard band is approximately 1.125 times the bit rate. The maximum power-limited data transmission rate for the link is

$$R_{maximum} = \frac{(C/N_o) \text{ available}}{(E_b/N_o) \text{ required}}, \text{ bps} \tag{4-2}$$

where

E_b/N_o = the energy-per-bit to noise-power-density ratio required by the data transmission technique to provide a specified fidelity.

For coherent QPSK modulation, a theoretical E_b/N_o of 6.8 dB is required to provide a bit error rate (BER) of 10^{-3}. A 1.2-dB implementation loss is assumed; thus, the required E_b/N_o is 8 dB.

Approximate SHF link analyses for the DSCS Phase II satellite used with FLTOPS, GMF, and DCS terminals are given in tables 4-2 through 4-6. The terminals marked with an asterisk in table 4-2 represent the particular terminal for each model to be used in link analysis. Tables 4-3 and 4-4 give the analyses of the up-links using the earth coverage and narrow-beam satellite antennas, respectively, while tables 4-5 and 4-6 give the analyses of the down-links using the earth coverage and narrow-beam satellite antennas respectively. The last line in each table gives the total number of 16-kb/s CVSD voice channels which could be supported by the satellite using the specified satellite antenna. In some cases the supportable bit rate is limited to 44.4 Mb/s by the exclusive 50-MHz bandwidth assumed, rather than by the available link power.

The transmitted effective isotropic radiated power (EIRP) and the ratio of receiving antenna gain to system noise temperature (G/T) are the "on-antenna-axis" values. Propagation losses associated with geographical factors, rain, and other factors are expressed by the average loss plus or minus twice the variance for each factor. The rain loss factor is calculated for an intensity of 25 mm/h. In calculating the power budget, the average received C/N_o is calculated (using the averages and the variance) by taking the sum of the squares of the individual variances.

Table 4-2. SHF Equipment Model.

TERMINAL	EIRP	G/T	NO OF CARRIERS (T/R)
GMF			
AN/TSC-85 (1-1/4 tons)	71 dB W	18 dB/°K	1/4
*AN/TSC-93	71 dB W	18 dB/°K	1/1
FLTOPS			
*AN/WSC-2	76 dB W	18 dB/°K	1/1
DCS			
*AN/MSC-60/FSC-78	97 dB W	39 dB/°K	9/12
AN/MSC-46	87 dB W	34 dB/°K	4/9
AN/MSC-61	92 dB W	34 dB/°K	3/4
AN/TSC-54	87 dB W	26.5 dB/°K	2/3

*Terminal used in link analysis.

Table 4-3. Typical SHF Up-Link Power Budget for DSCS II Satellite Using Earth Coverage Antenna.

ITEM		EARTH TERMINAL TYPE		
		FLTOPS	GMF	DCS
EIRP (on axis)	(dB W)	76.0	74.0	97.0
G/T (on axis)	(dB/°K)	-15.0	-15.0	-15.0
Geographical related losses	(dB)	-203.2 ±1.8	-203.2 ±1.8	-203.2 ±1.8
Rain-induced losses	(dB)	-1.2 ±1.2	-1.2 ±1.2	-1.2 ±1.2
Other independent losses	(dB)	-0.2 ±0.2	-0.2 ±0.2	-0.2 ±0.2
Temperature-to-noise-density conversion		228.6	228.6	228.6
Average Link C/N_o $\pm 2\sigma$	(dB-Hz)	85.0 ±2.2	83.0 ±2.2	106.0 ±2.2
C/N_o achieved 99.9% of time (3σ)	(dB-Hz)	81.7	79.7	102.7
Required E_b/N_o	(dB)	8.0	8.0	8.0
Supportable bit rate	(dB rel b/s)	73.7	71.7	94.7
	(in b/s)	23.4M	14.8M	*44.4M
Data rate per voice channel	(b/s)	16,000	16,000	16,000
Number of supportable voice channels		1,465	924	*2777

*Limited by bandwidth.

Table 4-4. Typical SHF Up-Link Power Budget for DSCS II Satellite Using Narrow-Beam Antenna.

ITEM		EARTH TERMINAL TYPE		
		FLTOPS	GMF	DCS
EIRP (on axis)	(dB W)	76.0	74.0	97.0
G/T (on axis)	(dB/°K)	-2.0	-2.0	-2.0
Geographical related losses	(dB)	-203.5 ±1.5	-203.5 ±1.8	-203.5 ±1.8
Rain-induced losses	(dB)	-1.2 ±1.2	-1.2 ±1.2	-1.2 ±1.2
Other independent losses	(dB)	-0.2 ±0.2	-0.2 ±0.2	-0.2 ±0.2
Temperature-to-noise-density conversion		228.6	228.6	228.6
Average link C/N_o $\pm 2\sigma$	(dB-Hz)	97.7 ±2.2	95.7 ±2.2	118.7 ±2.2
C/N_o achieved 99.9% of time (3σ)	(dB-Hz)	94.4	92.4	115.4
Required E_b/N_o	(dB)	8.0	8.0	8.0
Supportable bit rate	(dB rel b/s)	86.4	84.4	107.4
	(in b/s)	*44.4M	*44.4M	*44.4M
Date rate per voice channel	(b/s)	16,000	16,000	16,000
Number of supportable voice channels		*2777	*2777	*2777

*Limited by bandwidth

Table 4-5. Typical SHF Down-Link Power Budget for DSCS II Satellite Using Earth Coverage Antenna.

ITEM		EARTH TERMINAL TYPE		
		FLTOPS	GMF	DCS
EIRP (on axis)	(dB W)	28.0	28.0	28.0
G/T (on axis)	(dB/°K)	18.0	18.0	39.0
Geographical related losses	(dB)	-202.5 ±1.8	-202.5 ±1.8	-202.5 ±1.8
Rain-induced losses	(dB)	-1.4 ±1.4	-1.4 ±1.4	-1.4 ±1.4
Other independent losses	(dB)	-0.2 ±0.2	-0.2 ±0.2	-0.2 ±0.2
Temperature-to-noise-density conversion		228.6	228.6	228.6
Average link C/N_o ±2	(dB-Hz)	70.5 ±2.3	70.5 ±2.3	91.5 ±2.3
C/N_o achieved 99.9% of time (3σ)	(dB-Hz)	67.0	67.0	88.0
Required E_b/N_o (QPSK)	(dB)	8.0	8.0	8.0
Supportable bit rate	(dB rel b/s)	59.0	59.0	80.0
	(in b/s)	794,000	794,000	*44.4M
Data rate per voice channel	(b/s)	16,000	16,000	16,000
Number of supportable voice channels		50	50	*2777

*Limited by bandwidth.

Table 4-6. Typical SHF Down-Link Power Budget for DSCS II Satellite Using Narrow-Beam Antenna.

ITEM		EARTH TERMINAL TYPE		
		FLTOPS	GMF	DCS
EIRP (on axis)	(dB W)	43.0	43.0	43.0
G/T (on axis)	(dB/°K)	18.0	18.0	39.0
Geographical related losses	(dB)	-202.8 ±1.8	-202.8 ±1.8	-202.8 ±1.8
Rain-induced losses	(dB)	-1.4 ±1.4	-1.4 ±1.4	-1.4 ±1.4
Other independent losses	(dB)	-0.2 ±0.2	-0.2 ±0.2	-0.2 ±0.2
Temperature-to-noise-density conversion		228.6	228.6	228.6
Average link C/N_o $\pm 2\sigma$	(dB-Hz)	85.2 ±2.3	85.2 ±2.3	106.2 ±2.3
C/N_o achieved 99.9% of time (3σ)	(dB-Hz)	81.8	81.8	102.8
Required E_b/N_o (QPSK)	(dB)	8.0	8.0	8.0
Supportable bit rate	(dB rel b/s)	73.8	73.8	94.8
	(in b/s)	24M	24M	*44.4M
Data rate per voice channel	(b/s)	16,000	16,000	16,000
Number of supportable voice channels		1,500	1,500	*2777

*Limited by bandwidth.

4.2.2 SHF Traffic Models

Traffic information for each of the SHF users exists in several places. The COMSAT interim report (reference 1) on SHF TDMA modems contains a traffic model for FLTOPS. However, this traffic model reflects 5- to 10-year-old data and must be validated by data from other more recent sources. A second source for this traffic model is contained within CNO documents (reference 2) and substantiates the COMSAT FLTOPS traffic model data. Therefore, the COMSAT FLTOPS traffic model will be used in this report. For the GMF, the INTACS COMSR data base is used to derive the traffic model. The data base represents the traffic of the Army portion of the GMF for a midintensity general war scenario located in Europe. This traffic model represents planned traffic levels for the 1975 to 1985 time period.

The traffic model for DCS was derived from an ADL study (reference 4) on strategic communications in the European missions area. No second source was found for this traffic model. Because each of the three traffic models represent mean statistics only, ranges of value both above and below the mean are used to test the relative sensitivity of the study results to the traffic model.

4.2.2.1 FLTOPS SHF Traffic Model

The FLTOPS SHF traffic model used in this study was taken directly from the Naval deployment network model in the COMSAT (reference 1) report. Although this traffic reflects 10-year-old data, it was found to accurately model current FLTOPS traffic. Even the number of deployed terminals in the network represents currently identified deployment levels. The Naval deployment network was supplied by the Joint Tactical Communications Office and was combined with specific user data by TRI-TAC to form the FLTOPS traffic model. The actual network connectivity was derived from preassigned voice channels.

Figure 4-1 shows the network connectivity of the FLTOPS traffic model. It represents a deployed Naval Task Force located in mid-ocean with communication links back to supporting NAVCOMSTA's. It is assumed that the entire task force is served by a single SHF satellite at any one time. The busy hour traffic for each of the 22 network members is listed in table 4-7. The letters designating each node in table 4-7 correspond to the letters in figure 4-1. The total busy hour traffic for this model is approximately 32 Erlangs and represents 30, 3-minute calls per hour from each terminal. The composite network call rate is 0.18 calls per second for voice and an equal number of data calls. Assuming that the average data message contains 12,000 bits, then the total network data traffic is 0.92 Erlangs. Each network member has an AN/WSC-2 terminal which is assumed to operate at 16 kb/s for voice and 2400 b/s for data. Table 4-11 summarizes the FLTOPS SHF traffic model.

4.2.2.2 GMF SHF Traffic Model

It is essential to have accurate traffic models for evaluating and selecting the optimum DA systems in the DATS program. The traffic models used initially for the GMF in this study were derived for project MALLARD, and as such represented obsolete data. A subsequent program, the Integrated Tactical Communications System (INTACS) study, included more recent operational concepts and validated communications support requirements (COMSR) data bases. Therefore, an analysis of the INTACS COMSR data base will yield a more accurate up-to-date traffic model for the GMF than the project MALLARD data. The following paragraphs provide INTACS COMSR data base background, force model description, analysis technique descriptions, and a derived traffic model for the Army portion of the GMF.

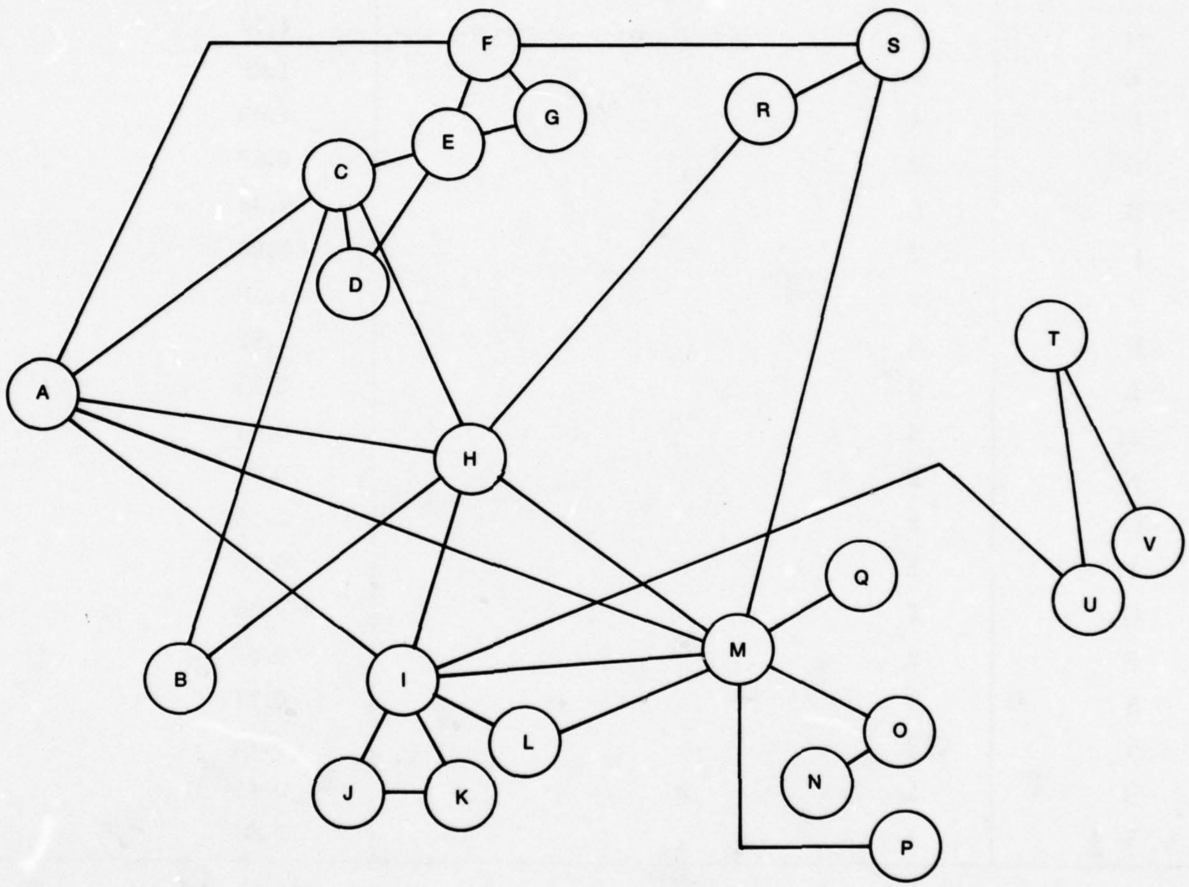


Figure 4-1. Naval Deployment Network.

Table 4-7. Naval Deployment Network Traffic.

NODE	TERMINAL CONNECTIVITY LINES	BUSY HOUR VOICE TRAFFIC (IN ERLANGS)
A	5	0.26
B	2	0.72
C	5	3.26
D	2	1.18
E	4	1.29
F	4	1.00
G	2	0.87
H	6	5.38
I	7	5.83
J	2	1.18
K	2	1.72
L	2	2.18
M	8	3.34
N	1	0.05
O	2	0.11
P	1	0.05
Q	1	0.36
R	2	0.87
S	3	0.77
T	2	0.72
U	2	0.41
V	1	0.36
Total		31.91 Erlangs

4.2.2.2.1 General Background

The communications support requirements (COMSR) program was the result of a Department-of-the-Army directed study effort. The purpose of the study, as stated in the study directive, was as follows:

a. USACDC, in coordination with other commands and the Army staff, will conduct the study to develop a program for determining communications support requirements. As an initial part of the program, USACDC will establish a requirements data base that can be

periodically refined and revised to reflect future changes in doctrine, deployment of forces, and equipment.

b. The study results will be used to implement a tactical communications support requirements program Army-wide. Additionally, the study will lead to the establishment of a data base that will be useful by all Army activities concerned with the analysis, design, development, and management of current and future communications systems.

The signal school conducted an analytical analysis of the COMSR data base. This entailed the comparison of the results of the COMSR study with the requirements information of other study efforts such as Army 75, MALLARD, Theater Army Comcunications 1970 (TACOM-70), and Communications Southeast Asia (COMSEA). This analysis indicated that user requirements reflected in the COMSR data base, overall, were lower than those developed in other studies.

4.2.2.2.2 The COMSR Force Model

The force model that was reviewed and analyzed in the development of COMSR data was a theater army on the European mainland. The force was comprised of a field army having five corps (three US and two allied), 15 US divisions, and the theater army administrative and logistical supporting troops. Only US Army elements were considered in the force model review and analysis. The main elements and enclaves of the theater army are shown in figure 4-2 representing a D+90 posture that extended from the shoreline at the rear of the COMMZ to the FEBA along the west bank of the Rhine River.

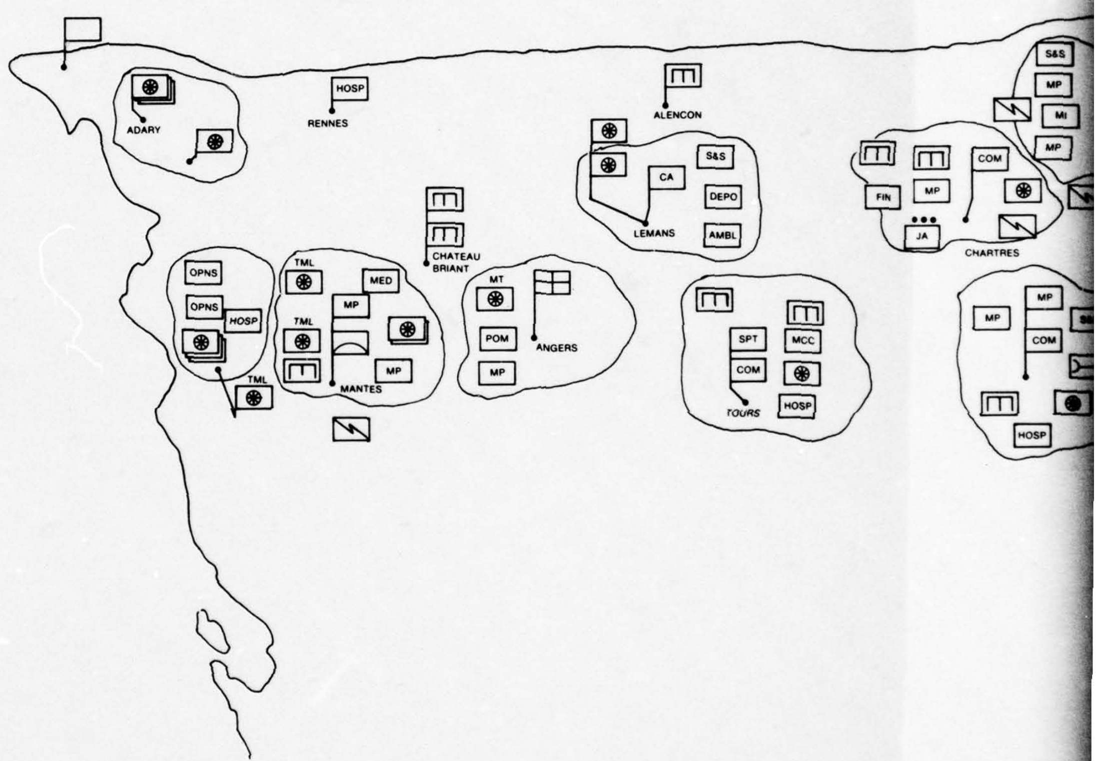
4.2.2.2.3 Analysis Methodology

The analysis of the COMSR data base was performed by using computer programs to determine the intensity of traffic that would be carried by satellite in the INTACS objective system. The COMSR data base contains the information necessary to derive traffic precedence, mode, intensity, and purpose of communications in the force model.

The analysis was conducted in two phases. The first phase was conducted to analyze multichannel (SHF) TACSATCOM which provides for long distance trunking within the division, corps, and theater army elements. The trunks are provided on a demand-assigned basis among AN/TTC-39 switches and MSE mobile subscriber centrals.

The second phase was to analyze single-channel TACSATCOM (UHF), also known as the minimum critical tactical communications (MCTC) system. The single-channel system provides critical command and control communications among key command posts from brigade through theater army level and is discussed in paragraph 4.3.2.2. The analysis procedure for both multichannel and single-channel TACSATCOM includes the following:

a. Identification of candidate nodes in the INTACS force model for support with TACSATCOM terminals. (These nodes are shown in the following models for multi- and single-channel.)
b. Using the force model, iterative execution of the computer programs were made to refine the initial network and traffic parameters from the COMSR data base.
c. A sensitivity analysis was used to determine effects of various force, node, and traffic factors on systems sizing.



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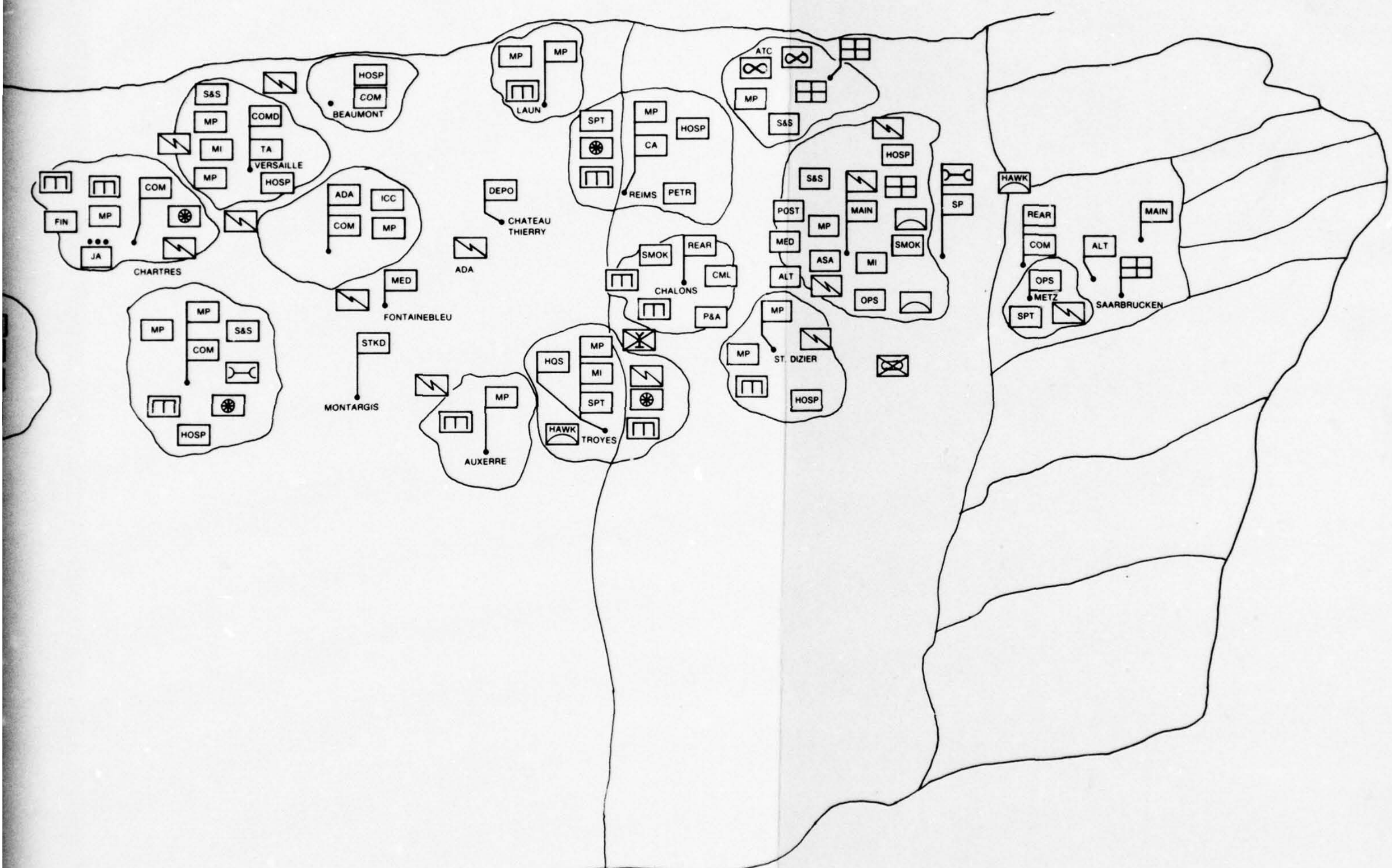

Figure 4-2. Theater Army Deployment.

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4.2.2.2.4 SHF Traffic Model

Figure 4-3 shows the baseline corps force model network for the INTAC corps used in the SHF traffic model. The interconnecting lines between nodes represent tentative command relationships rather than real communication-need lines. The diagram indicates that each corps contains a maximum of 18 nodes (terminals) plus additional nodes representing the adjacent corps and theater army elements. INTACS doctrine defines that traffic between these nodes will be considered SHF SATCOM if it falls into one of the following two groups:

a. Command and control traffic between any two nodes.
b. Administrative traffic between any two nonadjacent nodes (skip node).

Therefore, the analysis computer programs must count the traffic in the above two categories that flows between units located at different nodes. The final result must be multiplied by 3 to give the total traffic in any one satellite coverage area. Table 4-8 lists the busy hour voice and data traffic for each Center Corps node plus the two theater army nodes. The node numbers of table 4-8 and figure 4-3 are identical. A different presentation of the same data is given in table 4-9. Table 4-9 presents the total traffic for the Center Corps by precedence level, traffic type, traffic intensity, and number of messages.

From tables 4-8 and 4-9 the total busy hour voice traffic for all 60 nodes is 1532.1 Erlangs and the total busy hour data traffic is 41.4 Erlangs. The computed holding time for an

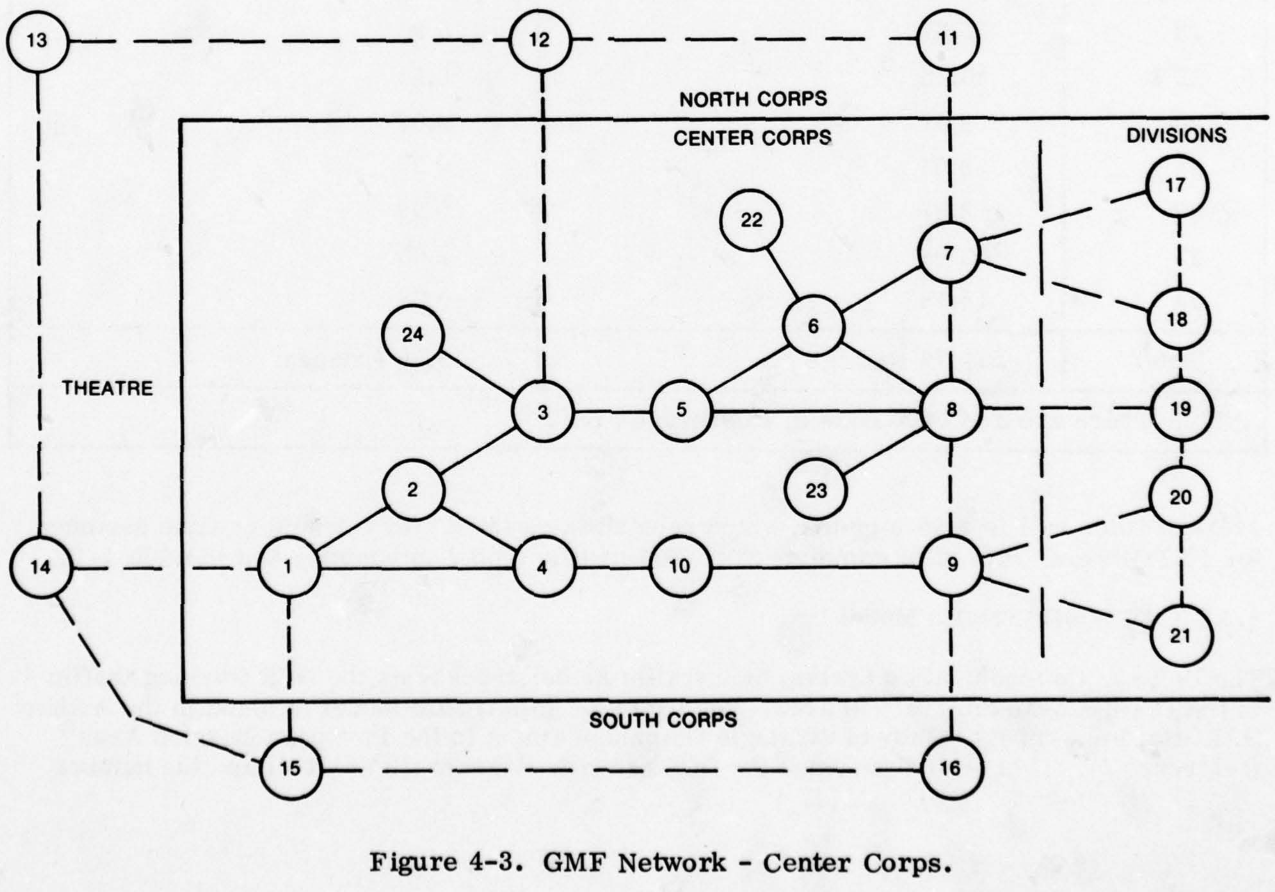


Figure 4-3. GMF Network - Center Corps.

Table 4-8. GMF Network Node Traffic.

NODE	BUSY HOUR VOICE TRAFFIC (IN ERLANGS)	BUSY HOUR DATA TRAFFIC (IN ERLANGS)
1	20.46	0.55
2	18.24	0.49
3	16.24	0.44
4	24.29	0.66
5	14.32	0.39
6	23.82	0.64
7	18.67	0.50
8	18.79	0.51
9	13.77	0.37
10	27.36	0.74
13	50.29	1.36
14	102.28	2.76
17	17.30	0.47
18	35.37	0.96
19	19.73	0.53
20	2.57	0.07
21	9.21	0.25
22	2.87	0.08
23	60.94	1.65
24	14.18	0.38
Total	510.70 Erlangs	13.80 Erlangs
Note: There are 3 of each node in a coverage area.		

average voice call is 2.96 minutes, which substantiates the 3 minutes holding time assumed for FLTOPS and DCS. The complete SHF GMF traffic model is summarized in table 4-11.

4.2.2.3 DCS SHF Traffic Model

The Defense Communication System SHF traffic model represents the DCS trunking traffic in the European-Mediterranean area. The basis for this traffic model is found in the Arthur D. Little, Inc., report "Study of Strategic Communications in the European Mission Area" (reference 4). This report provides the DCS network diagram (figure 4-4) and the number

Table 4-9. SHF Center Corps Traffic.

TRAFFIC (ERLANGS) (BUSY HOUR)	F_f	O_o	P_p	R_r	TOTAL
Voice	8.5	24.9	74.8	402.5	510.7
Record	0	0.2	0.4	1.3	1.9
Data	0	0.3	3.1	10.4	13.8
Facsimile	0.1	2.0	5.5	12.6	20.2
Total	8.6	27.4	83.8	426.8	546.6
NUMBER OF MSG (BUSY HOUR)	F_f	O_o	P_p	R_r	TOTAL
Voice	288	1,299	1,443	7,319	10,349
Record	1	179	459	206	845
Data	148	3,220	15,777	26,330	45,475
Facsimile	0	59	65	110	234
Total	437	4,757	17,744	33,965	56,903
NUMBER OF MSG (AVERAGE/HOUR)	F_f	O_o	P_p	R_r	TOTAL
Voice	119	213	593	3,021	3,946
Record	0	8	31	81	120
Data	31	167	419	6,707	7,324
Facsimile	0	10	16	31	57
Total	150	398	1,059	9,840	11,447

of terrestrial trunks serving each node. Then, by assuming that all these trunks are fully loaded during the busy hour, the total network traffic load can be calculated using the Erlang B traffic tables (assume 0.01 blocking). It is further assumed that 100 percent of this traffic will be carried by the satellite system. The results of these calculations are shown in table 4-10. Table 4-10 presents the busy hour voice traffic breakdown per network node. The average length for voice calls in this model is assumed to be 3 minutes.

From table 4-10, the busy hour voice traffic generated by the 21 nodes in the European DCS network is 861 Erlangs and is equal to a call rate of 4.78 calls/s. If an identical call rate is assumed for data along with an average message length of 12,000 bits, then the busy hour data traffic is equal to 23.92 Erlangs. Each node uses a data rate of 16 kb/s for each voice channel and 2400 b/s for each data channel. The entire DCS traffic model is summarized in table 4-11.

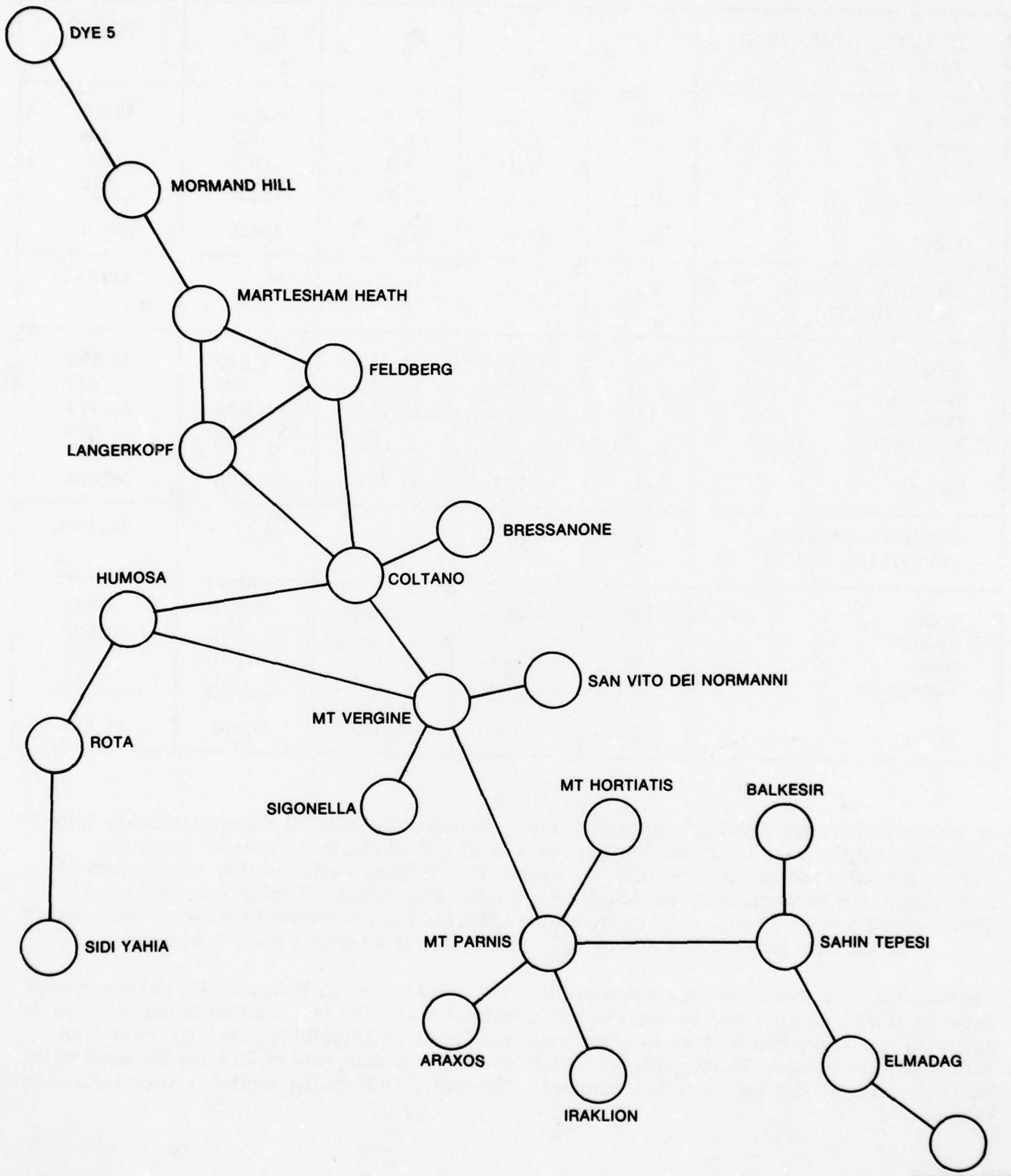


Figure 4-4. DCS European Network.

Table 4-10. DCS Nodal Voice Traffic.

COUNTRY	SITE	BUSY HOUR VOICE TRAFFIC (ERLANGS)
United Kingdom	Martlesham Heath	37.17
	Mormand Hill	37.17
Germany	Feldberg	123.88
	Langerkopf	174.47
Spain	Rota	12.39
	Humosa	74.33
Italy	Coltano	21.68
	Bressanone	4.13
	Mt. Vergine	49.55
	San Vito Dei Normanni	12.39
	Sigonella	12.39
Greece	Araxos	4.13
	Mt. Parnis	78.46
	Iraklion	24.78
	Mt. Hortiatis	12.39
Turkey	Balkesir	5.16
	Sahin Tepesi	27.87
	Elmadag	37.17
	Doyarbakir	24.78
Iceland	Dye 5	49.55
Morocco	Sidi Yahia	37.17
Total		861.01 Erlangs

4.2.3 Composite SHF User Models

Table 4-11 presents the SHF user models for FLTOPS, GMF (Army portion) and DCS. This table summarizes the data that was presented in paragraphs 4.2.2.1, 4.2.2.2, and 4.2.2.3. This information is used to evaluate the candidate SHF demand-assignment systems.

Table 4-11. SHF User Models.

PARAMETER (BUSY HOUR)	FLTOPS	GMF	DCS
Number of terminals (N)	22	60	21
Mean call rate/ terminal (λ') ($\lambda' = A/\overline{X}$)	30 calls/hour (voice) 30 calls/hour (data)	517 calls/hour (voice) 2274 calls/hour (data)	820 calls/hour (voice) 820 calls/hour (data)
Call rate/coverage area (λ)	0.18 call/second (voice) 0.18 call/second (data)	8.62 calls/second (voice) 37.9 calls/second (data)	4.78 calls/second (voice) 4.78 calls/second (data)
Mean Message length ($\overline{X}$) (holding time)	3 minutes (voice) 5 seconds (data)	2.96 minutes (voice) 1.09 seconds (data)	3 minutes (voice) 5 seconds (data)
Mean terminal traffic intensity (A')	1.5 Erlangs (voice) 0.04 Erlang (data)	25.54 Erlangs (voice) 0.69 Erlang (data)	41.0 Erlangs (voice) 1.14 Erlangs (data)
Coverage area traffic intensity (A)	32.0 Erlangs (voice) 0.92 Erlang (data)	1532.1 Erlangs (voice) 41.4 Erlangs (data)	861 Erlangs (voice) 23.92 Erlangs (data)
Blocking probability	0.01 (voice)	0.01 (voice)	0.01 (voice)
Data rate/ channel	16 kb/s (voice) 2,400 b/s (data)	16 kb/s (voice) 2,400 b/s (data)	16 kb/s (voice) 2,400 b/s (data)

4.3 UHF USER MODEL

The UHF users considered by this study are the Navy Fleet Operations (FLTOPS) and the Army Ground Mobile Forces (GMF). Because each of these users represent a community having many low-duty-cycle terminals that require netted communications, they are prime candidates to benefit from the application of demand-assignment. Therefore, these user models provide an excellent test vehicle for evaluating demand-assignment techniques.

Each user model was derived from a careful study of each community's network, data interfaces, traffic statistics (where available), communication requirements, existing and planned equipment deployment, and equipment deployment schedules. This data was compiled into two distinct categories, equipment models and traffic models. The data from these two models was combined to form the UHF user models which are used during evaluation of the candidate DA systems.

4.3.1 UHF Equipment and Link Models

Table 4-12 summarizes the terminal hardware for each of the UHF users. Only hardware which is already deployed or which will be deployed in the near future is listed. Included in table 4-12 are lists of the number of channels, EIRP, G/T, and bandwidth by terminal. These parameters, together with the satellite characteristics, are used to compute the up-link and down-link C/N_o values using equation 4-1.

The available end-to-end link C/N_o for an up-link and down-link combined is computed by

$$(C/N_o) = \frac{(C/N_o)_{up} \cdot (C/N_o)_{down}}{(C/N_o)_{up} + (C/N_o)_{down} + W} \qquad (4\text{-}3)$$

where W = the satellite transponder bandwidth, Hz, and the link C/N_o values have been converted from dB to ratio form.

For coherent binary phase-shift keying (BPSK) modulation, a theoretical E_b/N_o of 9.6 dB is required to provide a bit error rate (BER) of 10^{-5}. A 1-dB implementation loss is expected; thus, the required E_b/N_o is 10.6 dB.

The terminals marked with the double asterisk in table 4-12 indicate the terminal types for each model which are used in the link calculations. The typical FLTOPS equipment model is defined to represent a communication link between a small ship and a NAVCOMSTA. For the GMF, the equipment model represents a communication link between vehicular terminals. The results of the analyses for these links are shown in table 4-13, expressed in end-to-end C/N_o and associated transmission rate capacity. The miscellaneous losses value of 6 dB used in the calculations corresponds to a degraded condition of approximately two standard deviations from the mean C/N_o for these UHF links. Thus, the C/N_o values shown are expected to be exceeded more than 98 percent of the time. The transmission rates computed from equation 4-2 for these C/N_o values are also listed.

From table 4-13 it is observed that the expected transmission rate exceeds 4.8 kb/s for all transponder models and exceeds 9.6 kb/s for the FLTSAT link models listed. The user

Table 4-12. UHF Terminal Hardware Summary.

TERMINAL	NO OF CHANNELS	EIRP	G/T	BANDWIDTH
FLTOPS (Navy)				
** AN/WSC-5 with OE-82 antenna (large ship)	1 FDX 2 HDX	22 dB W minimum	-20 dB/°K	500 kHz
AN/WSC-3 with OE-82 antenna (small ship)	1 HDX	22 dB W minimum	-20 dB/°K	25 kHz
AN/WSC-3 with AN/BRA-34 antenna (submarine)	1 HDX	15 dB W	-30 dB/°K	25 kHz
P-3C with AN/ARC-143 R/T	1 HDX	18 dB W minimum	-30 dB/°K	25 kHz
S/3A with AN/ARC-156 R/T	1 HDX	18 dB W minimum	-30 dB/°K	25 kHz
TACAMO with AFSCS Type 1-X	2 FDX	27/17 dB W minimum	-29 dB/°K	500 kHz
**NAVCOMSTA with AN/WSC-5	2 FDX 6 HDX	22 dB W minimum	-15 dB/°K	500 kHz
Tactical support center with AN/ARC-143 R/T	1 HDX	30 dB W minimum	-18 dB/°K	25 kHz
GMF (Army)				
ETB - Force	1 HDX	28 dB W	-22 dB/°K -30 dB/°K*	500 kHz
ETB - CP	1 FDX	27 dB W	-23 dB/°K -31 dB/°K*	500 kHz
AN/PSC-( ) manpack	1 HDX	21 dB W	-23 dB/°K	25 kHz
**AN/MSC-( ) vehicular (VRS)	1 HDX	27 dB W	-22 dB/°K -30 dB/°K*	500 kHz

*Alert message reception only.

**Terminals used in link analysis.

models employed in the evaluation assume that FLTOPS networks will utilize 9.6 kb/s transmission where possible and will reduce to 4.8 or 2.4 kb/s transmission when required by terminal or propagation conditions. Current Army architecture calls for operation at 2.4 kb/s per channel, and this bit rate is therefore used in the user models employed in the evaluation of demand assignment candidates for UHF-GMF users, based primarily on reference 3 (INTACS COMSR data base).

The end-to-end C/N_o and associated transmission rate capability expected to be exceeded approximately 98 percent of the time are listed in table 4-13*.

Table 4-13. UHF Link Analysis.

MODEL	EARTH TERMINALS		SATELLITE TRANSPONDER AND BANDWIDTH					
	TRANSMIT	RECEIVE	FLTSAT (25 kHz)		GAPSAT (25 kHz)		GAPSAT (500 kHz)	
			C/N_o (dB)	RATE (kb/s)	C/N_o (dB)	RATE (kb/s)	C/N_o (dB)	RATE (kb/s)
FLTOPS	Small Ship AN/WSC-3	NAVCOMSTA AN/WSC-5	53.0	17.4	51.2	11.5	51.3	11.8
	NAVCOMSTA AN/WSC-5	Small Ship AN/WSC-3	51.6	12.6	49.4	7.6	49.4	7.6
GMF	Vehicular (VRS) AN/MSC-( )	Vehicular (VRS) AN/MSC-( )	52.6	15.9	50.0	8.7	52.0	13.8

4.3.2 UHF Traffic Models

Deriving a traffic model for FLTOPS turned out to be a relatively easy task. Similar traffic models were found in several US Government documents (references 5, 6, and 7) with the Lincoln Laboratory traffic model of J. Bridwell, et al, chosen because of its completeness.

Deriving the GMF traffic model was considerably more difficult because the traffic data did not exist at the start of the study. However, during this period, personnel at the US Army Signal School at Fort Gordon developed computer programs that could extract traffic model information from the INTACS (reference 3) COMSR data base. The data base represents the traffic of the Army portion of the GMF for a midintensity general war scenario located in Europe. The GMF traffic model represents planned traffic levels of the 1975 to 1985 time period and, hence, should accurately reflect planned GMF SATCOM traffic.

*Approximate propagation losses plus 6 dB (two standard deviations) for miscellaneous losses are 180.2 dB for up-links and 178.5 dB for down-links.

4.3.2.1 FLTOPS UHF Traffic Model

The two types of FLTOPS traffic that will use FLTSAT are data and voice. However, for this model all traffic will be considered data traffic because of the small amount of actual voice traffic. Data traffic will generally be buffered in order to increase system efficiency. Delivery times ranging from several minutes to several hours (depending on precedence) can be tolerated.

This model contains 10 large ships, 50 medium ships, and 100 small ships, all operating in the same satellite coverage area. Each large ship generates 2500 messages a day with each medium and small ship generating 250 messages a day and 25 messages a day, respectively. If all these messages are generated in a single 8-hour period, then the busy hour call rate is equal to 1.4 calls per second for the coverage area. The average length of each message is 12,000 bits and takes 1.2 seconds to send at 9600 b/s. For terminal sizing, it is assumed that the traffic intensity per terminal is uniformly distributed among the terminals and ranges from zero to twice the mean terminal traffic intensity. Table 4-16 summarizes the UHF FLTOPS traffic model.

4.3.2.2 GMF UHF Traffic Model

The GMF UHF traffic model was derived from the INTACS (reference 3) COMSR data base at Fort Gordon, Georgia. The COMSR data base reflects the communication requirement of the Army portion of the GMF traffic for a midintensity, general war scenario located in Europe. It assumes that there are three US corps consisting of 5 divisions each. The UHF traffic model reflects the single-channel communications between division and brigade levels for command and control traffic only. A complete description of the INTACS study and the COMSR data base can be found in paragraph 4.2.2.2 and its subparagraphs.

Figure 4-5 shows the 60-member baseline force model network for the UHF traffic model. The diagram represents the single-channel communications between the division and brigade levels for command and control traffic only. The terminals are located in command post vehicles and use existing I/O devices such as the TRTT and TRTP for record traffic interface. The following requirements were defined for establishing the UHF SATCOM traffic:

a. Command and control traffic between any two nodes of precedence level priority and higher.
b. No routine or voice traffic.

As in the SHF case, the final result must be multiplied by 3 to give the total traffic in any one satellite coverage area. Table 4-14 presents the results of the INTACS COMSR computer analysis and shows the priority-level data traffic by nodes. The numbers designating the nodes in table 4-14 have a "one-for-one" correspondence with the node numbers in figure 4-5. As indicated in the table, certain nodes only carry routine traffic (no priority traffic). Table 4-15 presents the same data in a slightly different fashion. It lists the UHF network traffic by data type, precedence level, traffic intensity, and message quantity.

Table 4-14 indicates that the total UHF data traffic generated by the 210 network members during busy hour is 12.6 Erlangs. This corresponds to a coverage area call rate of 3.69 calls/second or an average terminal call rate of 1.05 calls per minute. The computed mean message length is 8,170 bits and is transmitted at 2400 b/s. Table 4-16 summarizes the GMF UHF traffic model.

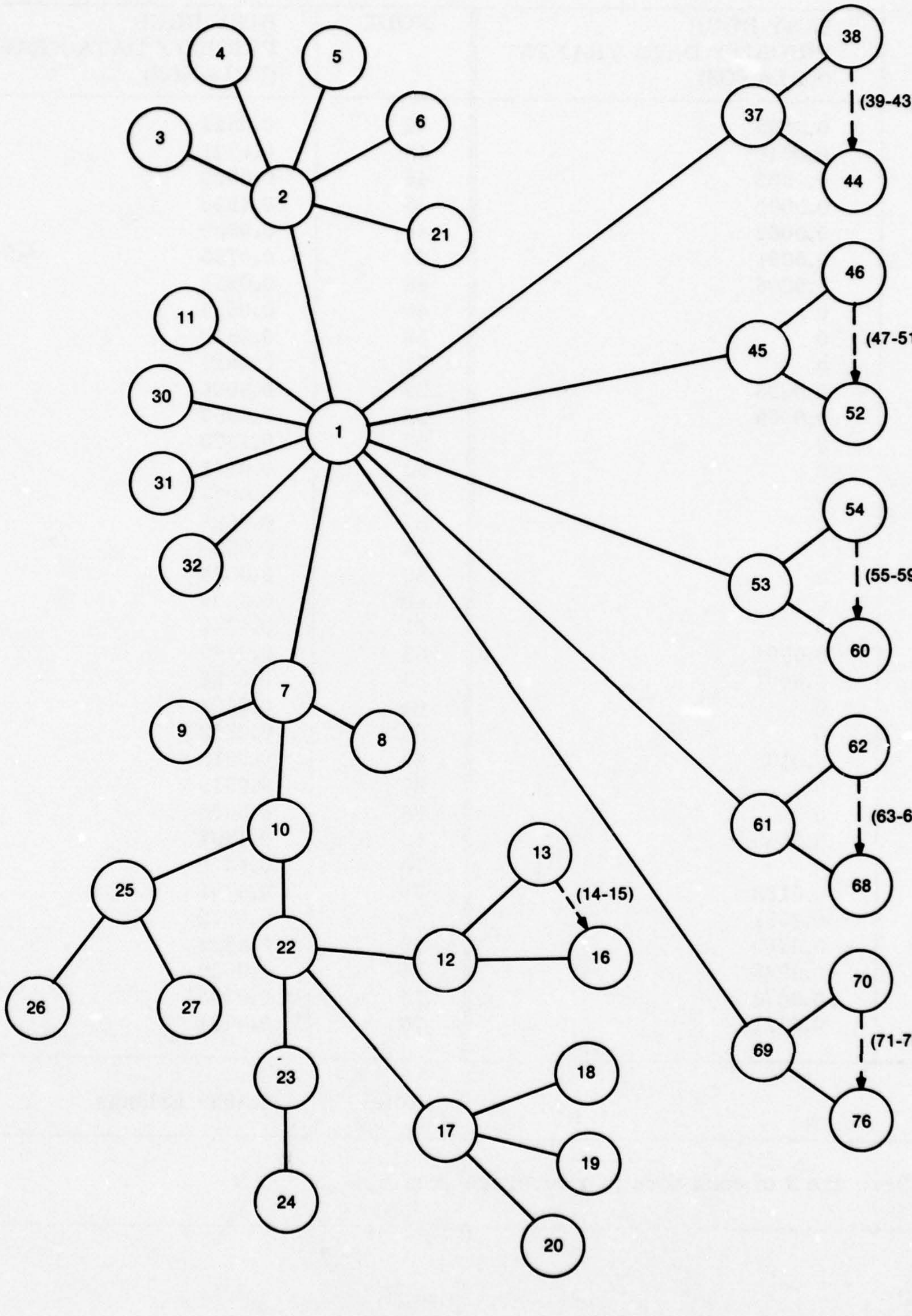


Figure 4-5. GMF UHF Network.

Table 4-14. GMF UHF Network Node Traffic.

NODE	BUSY HOUR PRIORITY DATA TRAFFIC (ERLANGS)	NODE	BUSY HOUR PRIORITY DATA TRAFFIC (ERLANGS)
1	0.2095	42	0.0321
2	0.0048	43	0.0321
3	0.0002	44	0.0002
4	0.0002	45	0.4240
5	0.0002	46	0.0999
6	0.0001	47	0.0735
7	0.0006	48	0.0031
8	0	49	0.0821
9	0	50	0.0820
10	0	51	0.0821
11	0.0638	52	0.0006
12	0.0009	53	0.4397
13	0	54	0.1370
14	0	55	0.0791
15	0	56	0.0017
16	0	57	0.0638
17	0	58	0.0639
18	0	59	0.0638
19	0	60	0.0004
20	0	61	0.4240
21	0.0004	62	0.0999
22	0.0001	63	0.0736
23	0	64	0.0031
24	0	65	0.0819
25	0.0135	66	0.0818
26	0	67	0.0819
27	0	68	0.0006
30	0.0015	69	0.4397
31	0	70	0.1370
32	0.0103	71	0.0791
37	0.2591	72	0.0172
38	0.0769	73	0.0638
39	0.0395	74	0.0639
40	0.0074	75	0.0638
41	0.0321	76	0.0004
		Total	4.1938 Erlangs

Note: There are 3 of each node in a coverage area.

4.3.3 Composite UHF User Models

Table 4-16 presents the UHF user models for FLTOPS and the Army GMF. The table summarizes the data presented in paragraphs 4.3.2.1 and 4.3.2.2. This data is used to evaluate the candidate demand-assignment systems for UHF.

Table 4-15. GMF UHF Traffic (Per Corps).

TRAFFIC (ERLANGS)	F_f	O_o	P_p	R_r	TOTAL
Record	0	0.01	0.09	0.21	0.31
Data	0.12	1.20	2.87	17.61	21.80
Facsimile	0	0.01	2.40	2.15	4.56
Total	0.12	1.22	5.36	19.97	26.67
NUMBER OF MSG (BUSY HOUR)	F_f	O_o	P_p	R_r	TOTAL
Record	1	5	34	67	107
Data	148	1,362	2,920	13,370	17,800
Facsimile	0	0	33	28	62
Total	149	1,367	2,987	13,465	17,969
NUMBER OF MSG (AVERAGE HOUR)	F_f	O_o	P_p	R_r	TOTAL
Record	0	1	7	13	21
Data	32	284	620	2,824	3,760
Facsimile	0	0	5	4	9
Total	32	285	632	2,841	3,790

Table 4-16. UHF User Models.

PARAMETER	FLTOPS	GMF
Number of terminals (N)	160 (10 large ships, 50 medium ships, 100 small ships)	210
Mean call rate/terminal (λ')	313 calls/hour/large ship 31 calls/hour/medium ship 3 calls/hour/small ship	1.05 calls/minute
Call rate/coverage area (λ) (busy hour)	1.4 calls/second	3.69 calls/second
Mean Message Length ($\bar{\ell}$)	12 kilobits	8.17 kilobits
Maximum waiting time (W_{max})	10 minutes	10 minutes
Transmission bit rate	9,600 b/s	2,400 b/s

4.4 REFERENCES

1. Communications Satellite Corporation, "Study of Functional Requirements for Demand Assignment SHF TDMA Modems," Interim Report, 24 May 1975.

2. US Navy, "Naval Telecommunications Systems Architecture 1975-1985," 1975.

3. Integrated Tactical Communications System (INTACS) Communications Support Requirements (COMSR) Data Base (A tool for analyzing, designing, and developing communication hardware used by the Department of the Army).

4. Arthur D. Little, Inc., "Study of Strategic Communications in the European Missions Area," ADL 09159, C13, 1974.

5. John D. Bridwell, et al, "A Preliminary Design of a TDMA System for FLEETSAT," ESD-TR-75-137, 12 March 1975.

6. Naval Electronics Systems Command, "System Specification for the Naval Modular Automated Communications System - System A+," NR1F001-00-AC, March 1974.

7. J. M. Aein and O. S. Kosovych, "On Capacity Allocation Strategies," IDA Log No. Hq 75-17866/2, 1976.

In this section we shall develop the general technical background required for analysis of the various candidate assignment systems, compare and discuss the merits and shortcomings of the various assignment techniques, and study the impact of other system parameters such as communications security (COMSEC), priority protocol, and diurnal traffic variations on system performance.

5.1 VOICE TRAFFIC HANDLING

Three baseband demand-assignment (BDA) and two demand-assignment multiple-access (DAMA) systems will be considered for voice traffic. The BDA systems considered are:

a. Baseband demand assignment with reservation (BDA-reservation)
b. Baseband demand assignment with time-assignment speech-interpolation (BDA-TASI).
c. Baseband demand assignment using slotted ALOHA random access (BDA-ALOHA).

The DAMA systems to be considered are:

a. Demand assignment multiple access with reservation (DAMA-reservation)
b. Demand assignment multiple access using slotted ALOHA random access (DAMA-ALOHA).

A subclass of DAMA-reservation which employs voice-operated transmitter activation (DAMA-VOX) will also be considered. This list includes the currently interesting generic types.

In comparing systems we shall be interested in minimizing the satellite channel capacity required to handle a specified intensity of offered traffic. The satellite capacity can be measured in terms of the required bandwidth or in terms of the required satellite power. The required bandwidth will be specified in terms of the number of equivalent voice channels.

For the user models considered, all voice traffic is digital, 16 kb/s continuously variable slope delta (CVSD) modulation. The grade of service is specified in terms of the maximum allowable blocking probability and the minimum acceptable voice quality imposed by the demand-assignment system. Following CCITT standards, the maximum allowable blocking probability is taken as 1 percent (reference 1). The minimum acceptable voice quality is reflected in a specified CVSD bit rate and in terms of the amount of speech sounds lost in TASI- and ALOHA-type systems due to contention. In keeping with CCITT standards, the voice traffic will be treated as lost calls cleared (reference 1). In practice this means that if a calling party is not connected, he will immediately hang up and will not repeat the call for several mean holding times.

5.1.1 Baseband Demand Assignment

In a BDA system, a terminal is assigned a fixed amount of channel capacity. The BDA terminal is involved with the assignment of incoming landline calls to the fixed channels on the

satellite link. In general, the fixed channels from any one terminal will be multiplexed together and transmitted on a single carrier on the satellite link. The same amount of power and bandwidth will be occupied by the terminal regardless of the number of off-hook customers the terminal is serving. The number of baseband channels required by a terminal (s')* as a function of the incoming traffic intensity per terminal (A')* is analyzed in appendix A and the results are shown in figure 5-1 for the BDA systems.

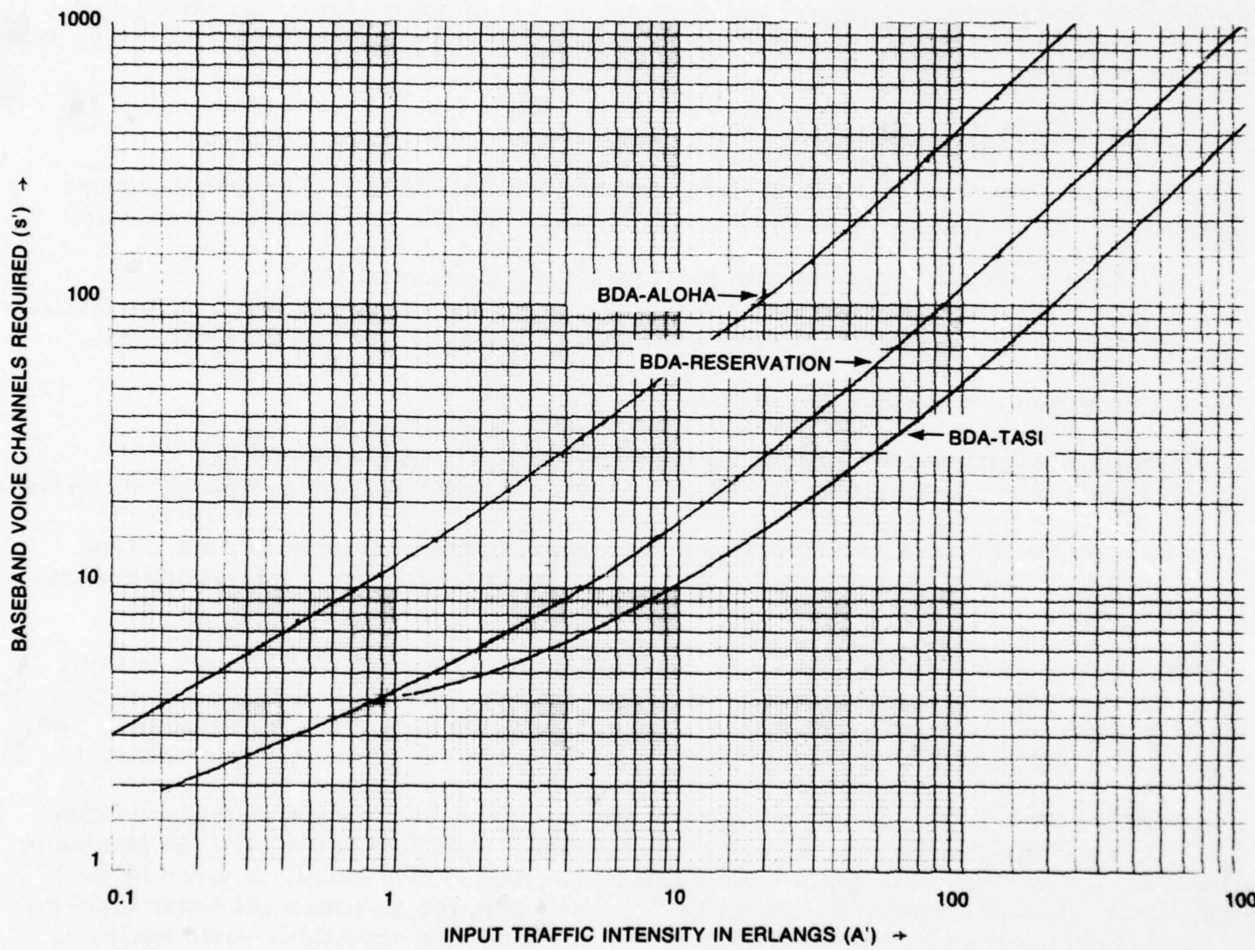


Figure 5-1. Number of Baseband Channels Required Versus Input Traffic Intensity for BDA Systems.

*The primes are used to indicate single terminal parameters, as contrasted with the total satellite network.

The standard BDA-reservation system is a BDA system in which baseband channels are assigned to incoming trunks for the duration of the call. In BDA-TASI, however, any baseband channel can be reassigned to a new incoming trunk if the speech activity on the old incoming trunk has ceased. TASI is a very dynamic form of BDA in which the voice channels are reassigned even during short pauses in the speech (references 2, 3, and 4). The TASI system shown is sized to give the voice quality obtained on standard TASI for undersea cables.*

A packet random access system can be used to provide access in a BDA system. This will be called BDA-ALOHA since it is basically a slotted ALOHA type system (reference 8). In this system the frequency channel is divided into a sequence of frames. Each frame is, in turn, divided into K time slots. A terminal transmits digital voice conversations by dividing the digital voice bit streams into a sequence of packets, each consisting of several hundred to several thousand digital speech bits. These packets are stored, for a time, and then transmitted as a short data burst in one of the time slots. Each packet contains a preamble indicating the destination (terminal and trunk number to which you are talking). All terminals monitor these preambles and store all received packets addressed to them in a buffer. This buffer is then read out at the proper time and data rate to the proper trunk number. In this system, packets are only transmitted when speech activity is present on the input line. A new packet is formed and transmitted each frame as long as there is speech activity present on the input line.

If the time slots within the frame were reserved for a given input line, then this would be a BDA-reservation system. In BDA-ALOHA, however, the time slots are not reserved and the terminal transmits these packets in time slots picked at random within each frame. If no other packet is transmitted in the same slot, then the packet gets through to the destination without error. However, if two or more packets are transmitted in the same time slot they will interfere with each other and both will be lost. Error detection codes are appended to the packets so that interference can be detected. If no more than 2 percent of the packets are lost, the grade of service will be approximately equal to TASI as used on overseas cables since these are designed for 1/2-percent freeze-out due to contention and 1-1/2-percent loss at the start of speech spurts.

It is shown in appendix A that for a 2-percent packet loss the number of simultaneous users can be maximized by transmitting each packet 6 times so that, if interference is absent on any one of the 6 tries, the packet will get through correctly.

From figure 5-1 it will be noted that as the input traffic intensity becomes very high BDA-TASI required only 40-percent of the number of baseband channels required by BDA reservation. This results from the fact that, on the average, speech is present on a full duplex line only 40 percent of the time.** When four or less baseband channels are used, BDA-TASI

*TASI is sized to provide a 1/2-percent loss due to contention. An additional 1-1/2-percent speech loss is incurred in present designs due to clipping of the start of speech spurts. In some TASI systems (SPEC) the number of voice waveform quantizing levels is reduced from 8 to 7 bits when overload occurs. With CVSD modulation, however, this technique is not applicable since CVSD at 16 kb/s is already operating with the lowest acceptable number of quantizing levels (reference 7).

**About 50 percent of the time a user is listening instead of talking and 10 percent of the time the user is pausing between words or phrases.

offers no savings over BDA-reservation. BDA-ALOHA is very inefficient, requiring 3-1/2 times as many channels as a BDA-reservation system.

The total number of satellite voice channels required for a network of BDA terminals (s) is the sum of the number of satellite voice channels required for the individual terminals. In BDA each satellite voice channel requires a fixed amount of satellite bandwidth and satellite average power.

5.1.2 Demand Assignment Multiple Access

In DAMA systems, satellite voice channels are pooled between all users in a network so that if a satellite voice channel is free it can be assigned to a user. There are no satellite channels permanently assigned to a particular terminal as in BDA. In DAMA-reservation, a terminal requiring another voice channel requests the assignment of a voice channel. This request is granted provided that a channel is available, and exclusive use of that channel is provided until the call is ended. A TASI-type system cannot be used with DAMA because of the long propagation delay on the orderwire channel. It is, however, possible to turn off the channel when there is no voice activity so as to save satellite power (but not bandwidth). This will be called DAMA-VOX.

A packet random access system can also be used to provide access in a DAMA system. This will be called DAMA-ALOHA since it is basically a slotted ALOHA type system (reference 8). In this system the satellite frequency channel is divided into a sequence of frames. Each frame is, in turn, divided into K time slots. A terminal transmits a digital voice conversation by dividing the digital voice bit stream into a sequence of packets consisting of several hundred to several thousand digital speech bits. These packets are stored, for a time, and then transmitted as a short data burst in one of the time slots. Each packet contains a preamble indicating the destination (terminal and trunk number to which you are talking). All terminals monitor these preambles and store all received packets addressed to them in a buffer. This buffer is then read out at the proper time and data rate to the proper trunk number. In this system packets are only transmitted when speech activity is present on the input line. A new packet is formed and transmitted each frame as long as there is speech activity present on the input line.

If the time slots within the frame were reserved for a given input line, then this would be a DAMA-VOX type system. In DAMA-ALOHA, however, the time slots are not reserved and the terminal transmits these packets in time slots picked at random within each frame. If no other terminal transmits a packet in the same slot, then the packet gets through to the destination without error. However, if another terminal transmits a packet in the same time slot they will interfere with each other and both will be lost. Error detection codes are appended to the packets so that interference can be detected. If no more than 2% of the packets are lost, the grade of service will be approximately equal to TASI as used on overseas cables since these are designed for 1/2-percent freeze-out due to contention and 1-1/2-percent loss at the start of speech spurts.

It is shown in appendix A that for a 2-percent packet loss the number of simultaneous users can be maximized by transmitting each packet 6 times so that, if interference is absent on any one of the 6 tries, the packet will get through correctly.

DAMA-reservation, DAMA-VOX, and DAMA-ALOHA are currently the most attractive generic DAMA methods for satellite voice service and these will therefore be considered. The analysis of these systems is presented in appendix A. The total number of satellite channels (s)

required to provide the specified grade of service (1 percent blocking probability and 2 percent maximum speech loss due to contention) as a function of the total offered traffic intensity from all terminals (A) is shown in figure 5-2. For DAMA-reservation and DAMA-VOX the number of satellite channels is obtained directly from the Erlang B equation for lost calls cleared (reference 9) at a 1 percent blocking probability. For DAMA-ALOHA the maximum number of simultaneous busy lines is obtained for the specified input traffic intensity using the Erlang B equation for a 1 percent blocking probability. The number of time slots required per frame for a 2 percent packet loss is then calculated for this number of busy lines using the algorithms developed in appendix A, using the optimum number of packet repetitions of six. The number of TDMA satellite voice channels required is of course just equal to the number of time slots per frame, since one slot per frame is capable of handling one voice channel in a fixed-assignment type system.

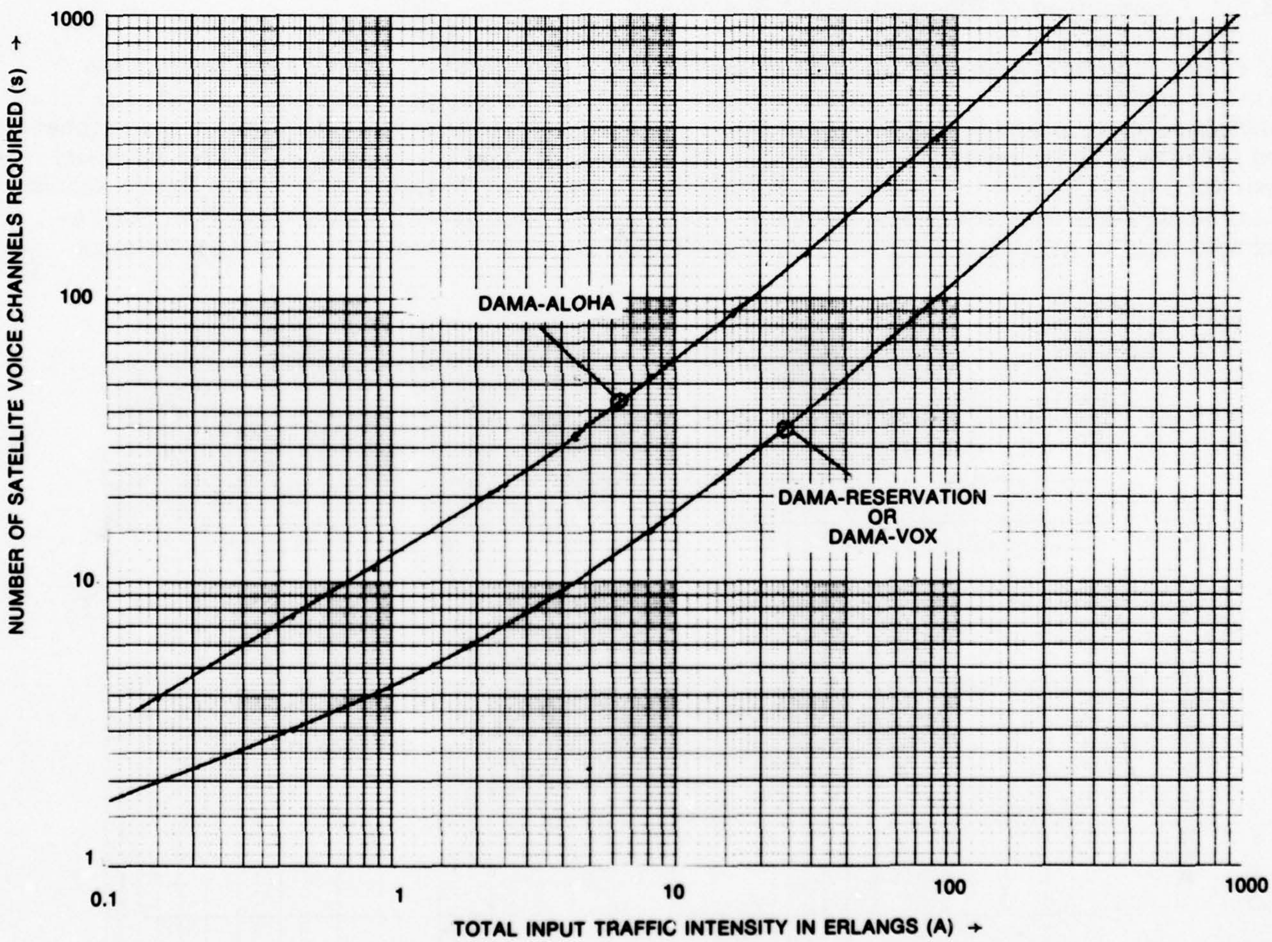


Figure 5-2. Number of Satellite Channels Required Versus Input Traffic Intensity for DAMA Systems.

Figure 5-2 reflects the satellite bandwidth required in terms of the number of voice channels required. The average satellite power required by a DAMA-reservation system is reduced by 4 dB in DAMA-VOX since the channel is active only 40 percent of the time (-4 dB). In appendix A it is shown that for DAMA-ALOHA only 52 percent of the time slots are filled on the average when the maximum number of simultaneous users are active. Therefore, the average satellite down-link power is reduced by 2.8 dB below that required if all slots were fully occupied so that DAMA-ALOHA requires 2.8 dB less average power than is indicated by the number of satellite channels.

From figure 5-2 it will be noted that DAMA-ALOHA requires 3-1/2 times (5.4 dB) as many satellite channels as needed for a DAMA-reservation or DAMA-VOX system. Applying the correction factors to obtain relative average required satellite powers, it is found that DAMA-ALOHA requires 5.4 - 2.8 or 2.6 dB more average power than DAMA-reservation and 5.4 - 2.8 + 4.0 or 6.6 dB more average power than DAMA-VOX.

5.1.3 Comparison of BDA and DAMA Systems

It is instructive to compare the best of the BDA systems (BDA-TASI) with the best of the DAMA systems (DAMA-reservation and DAMA-VOX). To compare BDA and DAMA, the baseband voice channel requirements for a single terminal must be multiplied by the number of terminals in the network. The results will depend on both the busy-hour traffic intensity per terminal (A') and the number of terminals (N) as shown in figure 5-3. This figure shows that BDA-TASI requires fewer channels and therefore less satellite bandwidth than DAMA-reservation in all cases where the input traffic intensity per terminal exceeds 10 Erlangs.

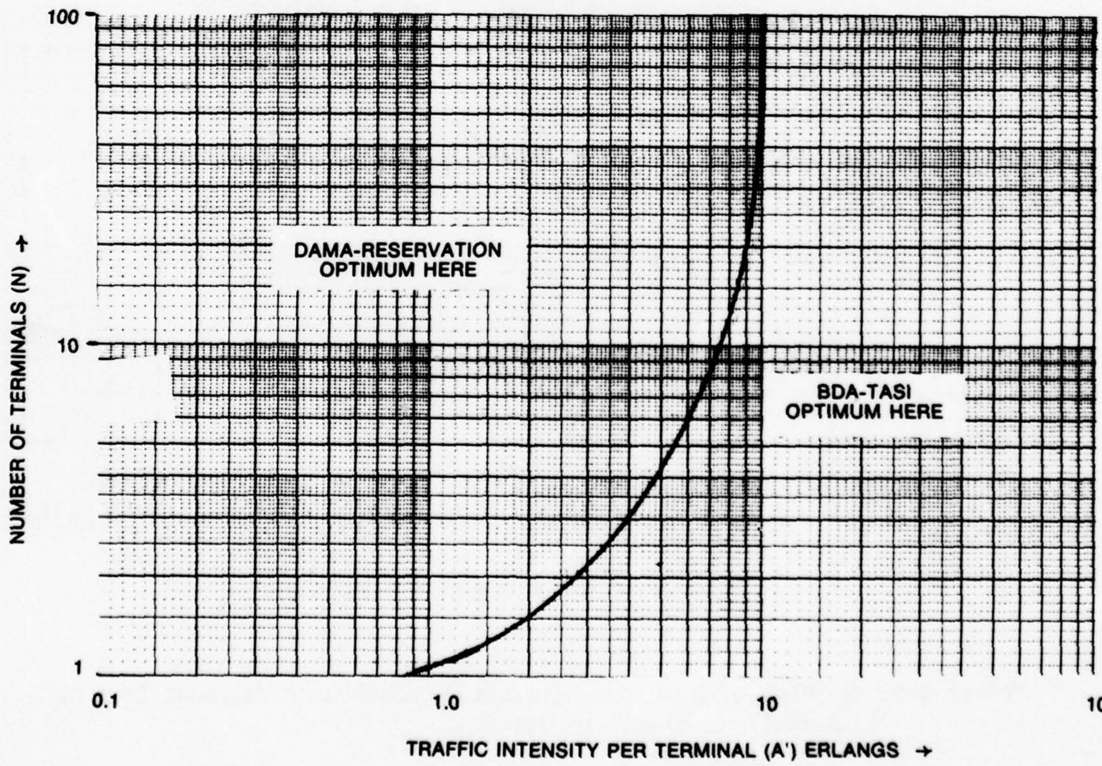


Figure 5-3. Areas for Minimum Satellite Channels Using BDA-TASI and DAMA-Reservation Systems.

It should be noted, however, that the above assumes that all terminals have the same input traffic, that the busy hour occurs at the same hour for all terminals, that the traffic statistics are known exactly a priori for the terminals, and that the TASI system is designed with exactly the optimum number of baseband channels. For DAMA-reservation, these factors do not affect the design, and only the total traffic intensity is important. Therefore, in actual practice, DAMA-reservation is more flexible than BDA-TASI, and the performance of BDA-TASI may be poorer than the ideal system treated here.

In terms of required average satellite power, DAMA-VOX will always outperform BDA-TASI by some margin because DAMA-VOX is equivalent to TASI but allows pooling of a larger number of channels, which will provide somewhat better performance.

Hybrid BDA/DAMA systems are also possible. For example, BDA-TASI can be used for the larger terminals in a network and DAMA-VOX could be used for the smaller terminals. It is also possible to utilize a DAMA-reservation system to continuously change the number of channels assigned to BDA-TASI terminals.

5.1.4 Calculation of Voice Traffic Channel Requirements

For BDA systems, the total number of voice circuits is obtained by first finding the number of voice circuits required for each terminal using the busy-hour traffic intensity for that terminal in conjunction with figure 5-1. The total number of voice circuits required for the satellite network is obtained by summing together the number of voice circuits required for each terminal.

For DAMA systems, the total busy-hour traffic intensity is obtained by summing the traffic intensities of the individual terminals. If the time zone spread between terminals is large, the busy-hour traffic intensity is reduced by a correction factor caused by diurnal traffic variations as discussed in paragraph 5.3.1. This corrected total busy-hour traffic intensity is used in conjunction with figure 5-2 to obtain the total number of voice circuits required for the satellite network.

If data traffic is to be handled as switched traffic, the data traffic intensity in Erlangs, A_D', for a terminal can be added to the voice traffic intensity in Erlangs, A_V', for that terminal to obtain the total traffic intensity in Erlangs, A_T', for that terminal, or

$$A_T' = A_D' + A_V'. \tag{5-1}$$

The data traffic intensity, A_D', for a terminal can be calculated from the terminal message generation rate, λ_D', the mean message length in bits, $\bar{\ell}$, and the channel bit rate, r, by

$$A_D' = \lambda_D' \cdot \bar{\ell}/r. \tag{5-2}$$

In addition to voice and data traffic, allowances must also be made for control traffic. For TASI, one control circuit is generally required for every 25 voice circuits. In addition, control traffic is required for initial establishment of a switched circuit for voice and data.

5.2 DATA TRAFFIC HANDLING

While data can be handled along with voice as switched traffic, it is often more efficient to treat data as store-and-forward traffic in which data messages are stored up in a waiting line or queue until the channel capacity to transmit that traffic is available. We shall be concerned here with the efficiency of the various methods of assigning the channel capacity of the satellite to the messages and of regulating the queue for store-and-forward traffic.

The following candidates are considered:

a. Reservation assignment with a slotted ALOHA orderwire.
b. Reservation assignment with a TDMA orderwire.
c. Polled assignment.
d. Random assignment using slotted ALOHA.
e. Fixed-assignment FDMA.
f. Fixed-assignment TDMA.

These candidate assignment systems are listed in table 5-1 and are analyzed in detail in appendix B. In store-and-forward operations, the BDA technique is the discipline used in handling the store-and-forward queue. BDA is, therefore, and intrinsic part of store-and-forward systems and will be addressed as a separate issue under priority protocol. Pure ALOHA is not considered because slotted ALOHA will give better performance in all cases (appendix B). Our objective is to maximize the busy-hour traffic capacity of the communications system in some sense or, alternately, to minimize the channel capacity required for a fixed busy-hour traffic intensity while providing an acceptable grade of service. We shall be primarily concerned here in maximizing the number of users which can be accommodated on a given satellite channel during the busy hour while providing an acceptable system waiting time.

5.2.1 Traffic Capacity With Specified Maximum Mean Waiting Time

The system waiting time is the time elapsed from the submission of the entire message at the transmitting terminal to the successful reception of the entire message at the receiving terminal. The mean system waiting time, W, has been analyzed for each of the candidate assignment systems in appendix B. The number of users or terminals that a satellite channel will support, using a particular assignment technique, is found by applying the equations to the user models. We will assume that the message length, ℓ, is exponentially distributed and that the message interarrival times are random and exponentially distributed. The parameters of all candidate assignment systems have been chosen so as to maximize the traffic capacity for a specified mean system waiting time. The results are, therefore, the best that can be achieved within the constraints of the generic assignment system type.

5.2.1.1 General Discussion of Assignment Systems

The system waiting time is composed of two parts. The first part is the time spent waiting in line or queue until a customer (message) can obtain service (a communications channel) and is known as the queue waiting time. After service is obtained, one must still wait until the service (message transmission) is completed. This second part is known as the service time. There are several methods of assigning channels to messages. In the first method, each terminal is assigned a small fraction of the total channel capacity by use of time or frequency-division multiple access. This is known as fixed assignment. In this case, if a particular terminal has a long queue of store-and-forward traffic while another terminal is idle, the busy terminal cannot use the idle channel capacity, and the unused channel capacity is wasted. If all terminals maintain a backlog of business, there is little capacity wasted. However, even when a message gets a channel, the message service rate will be low because the channel capacity is shared among the users and the service waiting time will therefore be long.

In reservation assignment, any available channel capacity can be assigned to any user so that channel capacity is not wasted if available. There are, however, two ways of sharing the channel capacity. In the first method, all the server or channel capacity is grouped together as a single high-speed server. In this case, the service waiting time is very short. Alternately

Table 5-1. Assignment System Parameters.

SYSTEM TYPE	ASSUMED SYSTEM PARAMETERS
Reservation assignment plus random-assignment slotted ALOHA orderwire	Message preamble: 120 bits Reservation message: 120 bits
Reservation assignment plus fixed-assignment TDMA orderwire	Message preamble: 120 bits Reservation message: 120 bits
Polled assignment	Gaps between user transmission: 1/4 second = 1,200 bits.
Random-assignment slotted ALOHA	Packet preamble: 120 bits Information bits per packet: 1,680 bits* Random retransmission spread: 15 slots*
Fixed-assignment FDMA (ideal)	Capacity loss due to multiple access: None.
Fixed-assignment TDMA	Packet preamble: 120 bits Information bits per packet: 1,680 bits*

*These parameters were chosen to maximize traffic capacity for a mean message length, $\bar{\ell}$, of 12,000 bits and a system waiting time, w, of 48 mean message lengths.

the total channel capacity can be divided up into a number of servers by means of FDMA or TDMA. In this case, the bit rate of any service channel is a small fraction of the total channel capacity, and the service waiting time will be long. The queue waiting time of these two systems is the same. In reservation assignment, an orderwire or control channel is required to make reservations, and this may significantly reduce the channel capacity available for message traffic.

Each data message must be preceded by a preamble which contains message type, priority, and routing information. This preamble length, a_1, is typically 120 bits. The mean message length, $\bar{\ell}$, is typically 12000 bits long so that the ratio of the message preamble to the mean message length, $a_1/\bar{\ell}$, is 0.01. A reservation request also contains the message type, priority, and routing information. The reservation request length, a_2, is typically 120 bits so that the ratio of the reservation length to the mean message length, $a_2/\bar{\ell}$, is typically 0.01.

In polled assignment, each terminal stores its message backlog in a local queue. Each terminal transmits sequentially in turn. Once transmission starts, it is continued until the message queue for that terminal is empty; then the channel is handed over to the next terminal in sequence. This system requires some overhead channel capacity to pass control from one station to the next. This overhead traffic is very significant and causes a significant increase

in the mean queue waiting time for light traffic loads. For heavy traffic, however, every terminal accumulates a large backlog of traffic and holds the channel for an appreciable length of time. While the mean queue waiting time becomes long, it is no longer than any other system since the overhead channel capacity becomes only a small fraction of the total. One disadvantage of a polling system, compared to a reservation system, is that priority protocol cannot be exercised in the network as a whole but only on the individual terminal queues.

For polled assignment, one must wait until the end of the transmission of the terminal that precedes you is received before transmission of your message queue can start. The satellite channel will, therefore, be unoccupied from the time that the end of the previous message leaves the satellite until the beginning of the new message arrives at the satellite. This time is the round trip propagation time of 1/4 second. The number of bit times for which the satellite channel is idle, d, is therefore 1/4 of the bit rate. For a bit rate of 4800 b/s, d is 1200 bits and the ratio $d/\bar{\ell}$ is 0.1.

In random-assignment systems, a terminal broadcasts whenever it has a message. If the traffic intensity is very low, this provides extremely fast access to the service channel. However, if any appreciable amount of traffic is handled, the terminals will interfere with each other and numerous message repeats will be necessary. At most, random assignment can handle traffic at a rate of only 37 percent of the channel's capacity. This is achieved by requiring that the messages be transmitted as short packets, and at random but within the constraints of a time slot. This system is known as slotted ALOHA.

Each slotted ALOHA packet must have a preamble. The typical length of this preamble, a, is 120 bits so that $a/\bar{\ell}$, is 0.01. The optimum number of information bits per packet, b, for a mean message length, $\bar{\ell}$, of 12000 bits and a preamble, a, of 120 bits of 1680 bits. K time slots are grouped together to form a frame and, when retransmission is required, one of the K time slots in the frame is picked at random for the retransmission of the packet. A near optimum value of K is 15 (reference 8).

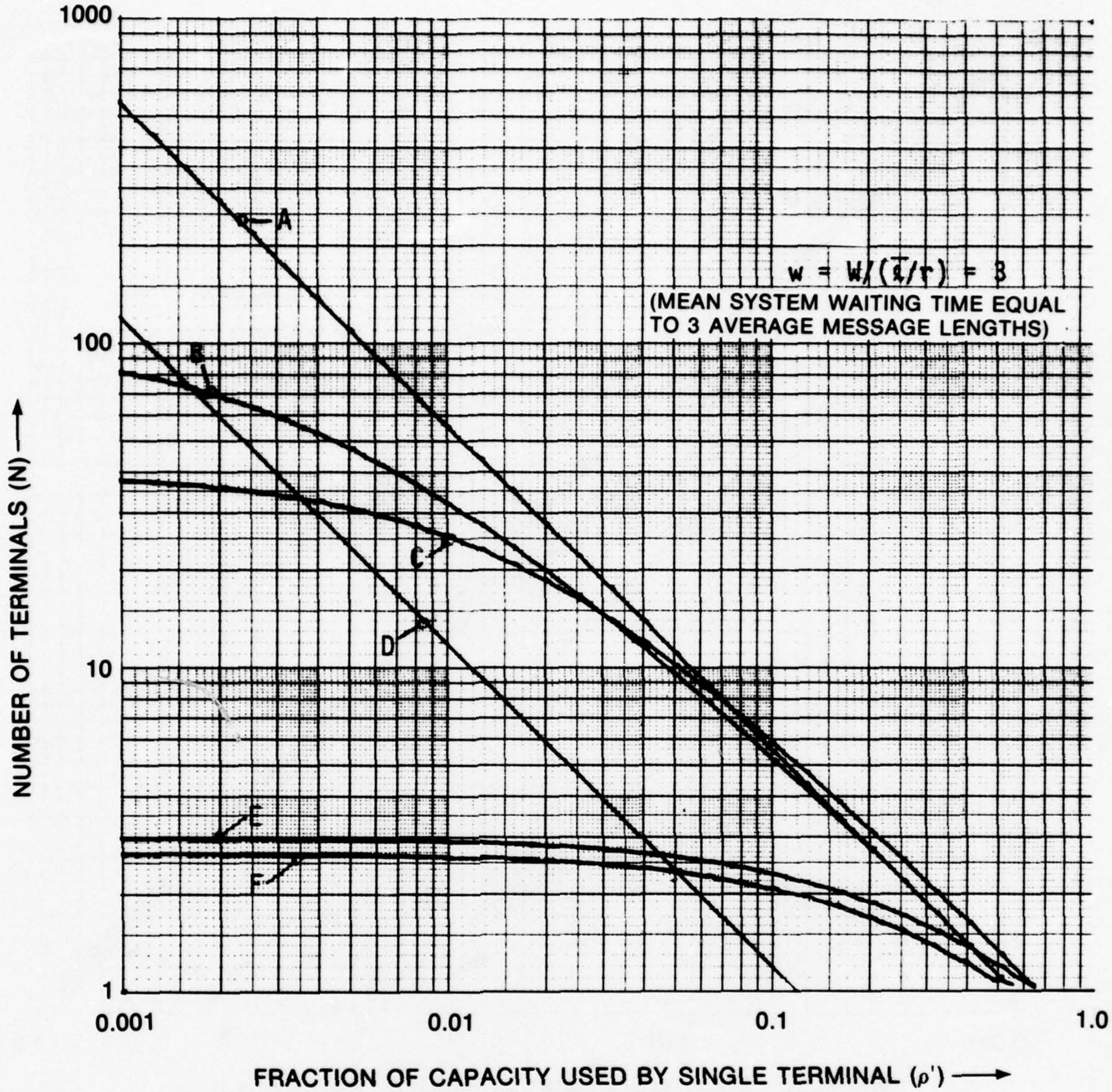
The performance of a fixed-assignment FDMA system depends very heavily on the characteristics of satellite repeater, and not on the DAMA system alone. We have, therefore, considered an idealized FDMA system for the current discussion. For fixed-assignment TDMA we have assumed a packet preamble length, a, of 120 bits and the optimum number of information bits per packet of 1680 bits.

5.2.1.2 Comparison of Assignment System Performance

Typical performance curves for the six candidate systems are shown in figures 5-4 and 5-5. For these graphs, the system parameters are as shown in table 5-1 with a 12,000-bit mean message length, $\bar{\ell}$, and with a bit rate, r, of 4,800 bits per second. The equations used are derived in appendix B and the appropriate equation numbers are given in the legend of the figures. These curves are plotted showing the number of terminals, N, that can be accommodated vs the fraction of the total satellite capacity used by each terminal to transmit information*, ρ'. The mean system waiting time is 3 and 100 mean message lengths, respectively, for figures 5-4 and 5-5. The relative standing of the assignment systems depends upon the system parameters.

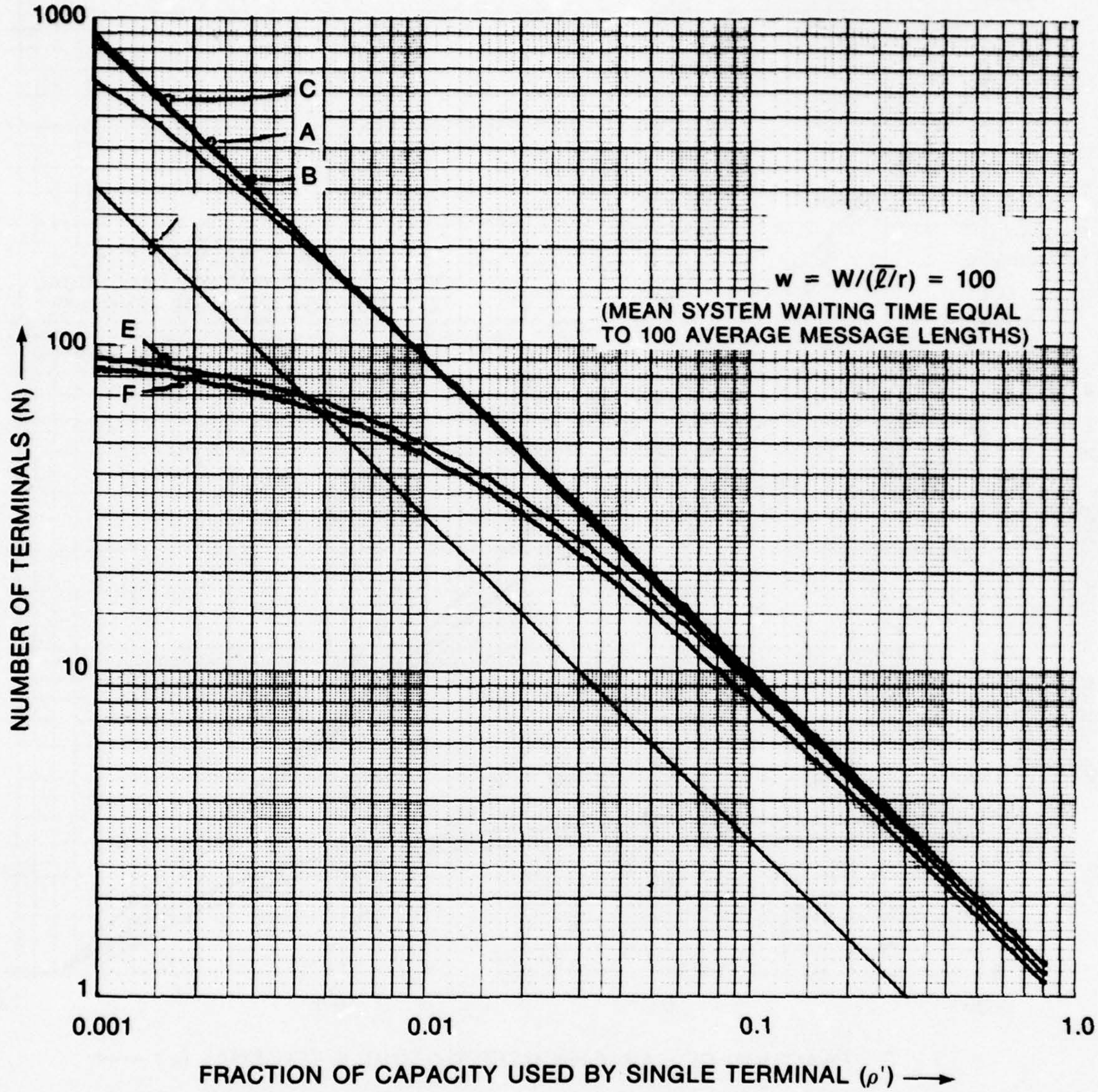
For the parameters chosen, it will be noted that for low-duty-cycle users the reservation-assignment system will support the largest number of users with the specified mean system

*This will also be referred to as the user or terminal duty cycle.



LEGEND		
CURVE	TYPE SYSTEM	EQ. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED	B-37
D	SLOTTED ALOHA	B-41
E	FDMA	B-32
F	TDMA	B-34

Figure 5-4. Comparison of Systems for w=3 for Random Length Messages With Random Arrivals. w=Normalized System Waiting Time in Message Lengths = W/($\bar{\ell}$/r).



LEGEND		
CURVE	TYPE SYSTEM	EQ. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED	B-37
D	SLOTTED ALOHA	B-41
E	FDMA	B-32
F	TDMA	B-34

Figure 5-5. Comparison of Systems for w=100 for Random Length Messages With Random Arrivals. w=Normalized System Waiting Time in Message Lengths = $W/(\bar{l}/r)$.

waiting time. For extremely low-duty-cycle users, a slotted ALOHA-type orderwire accommodates more users than a TDMA orderwire. As the user duty cycle increases, the performance of the polled system approaches that of the reservation systems. Finally, as the user duty cycle approaches unity, the performance of the two fixed-assignment systems approaches that of the polled and reservation-assignment systems. In this particular example, the performance of the slotted ALOHA system never approaches that of a reservation-assignment system. The slotted ALOHA system does, however, accommodate the largest number of users for a very low user duty cycle when the mean system waiting time is between 1.2 and 1.3 message lengths. The polled system will accommodate the largest number of users for long mean message waiting times and moderately high user duty cycle.

The system that gives the minimum mean system waiting time, W, for each area in the N vs ρ' plane is shown in figure 5-6. It will be noted that reservation assignment with a slotted ALOHA orderwire gives the minimum W for a large number of low-duty-cycle users, and polled assignment gives the minimum waiting time for a small number of high-duty-cycle users. Fixed-assignment FDMA is optimum for a single user.

5.2.2 Traffic Capacity With Specified Maximum Waiting Times

In the case of military data traffic, it is usual to specify the maximum desired waiting time for each priority class of traffic. With Poisson distributed message arrivals and exponentially distributed message service times, there is no upper limit on the waiting time in the store-and-forward traffic handling system. It is therefore impossible to guarantee that some maximum system waiting time for a given priority class will never be exceeded. It is possible, however, to specify a maximum desired system waiting time for each priority class which is not to be exceeded for more than a specified percent of the messages. This situation has been analyzed in paragraph 5.3.6 for Poisson distributed message arrivals and exponentially distributed message lengths with additional waiting time added for making reservations.

If no priority protocol is used, all messages must be handled with the same expediency and must therefore be delivered in the time specified for the highest priority messages.

5.3 FACTORS IN THE DETAILED COMPARISON OF TRAFFIC HANDLING SYSTEMS

There are a number of factors that must be considered in the detailed comparison of traffic handling systems. These details include the following:

a. Diurnal traffic intensity variations.
b. Terminal-to-terminal traffic intensity variations.
c. Channel and hardware quantization.
d. Switched versus store-and-forward traffic handling.
e. Communications security.
f. Priority protocol.
g. Common channel versus in-band signaling.
h. Central versus distributed control.

These factors are discussed in the following paragraphs.

5.3.1 Diurnal Traffic Intensity Variations

A typical voice traffic intensity variation through the day is bimodal, having approximately equal peaks at 10:30 am and 4:30 pm local time and having a peak traffic intensity of 3 times

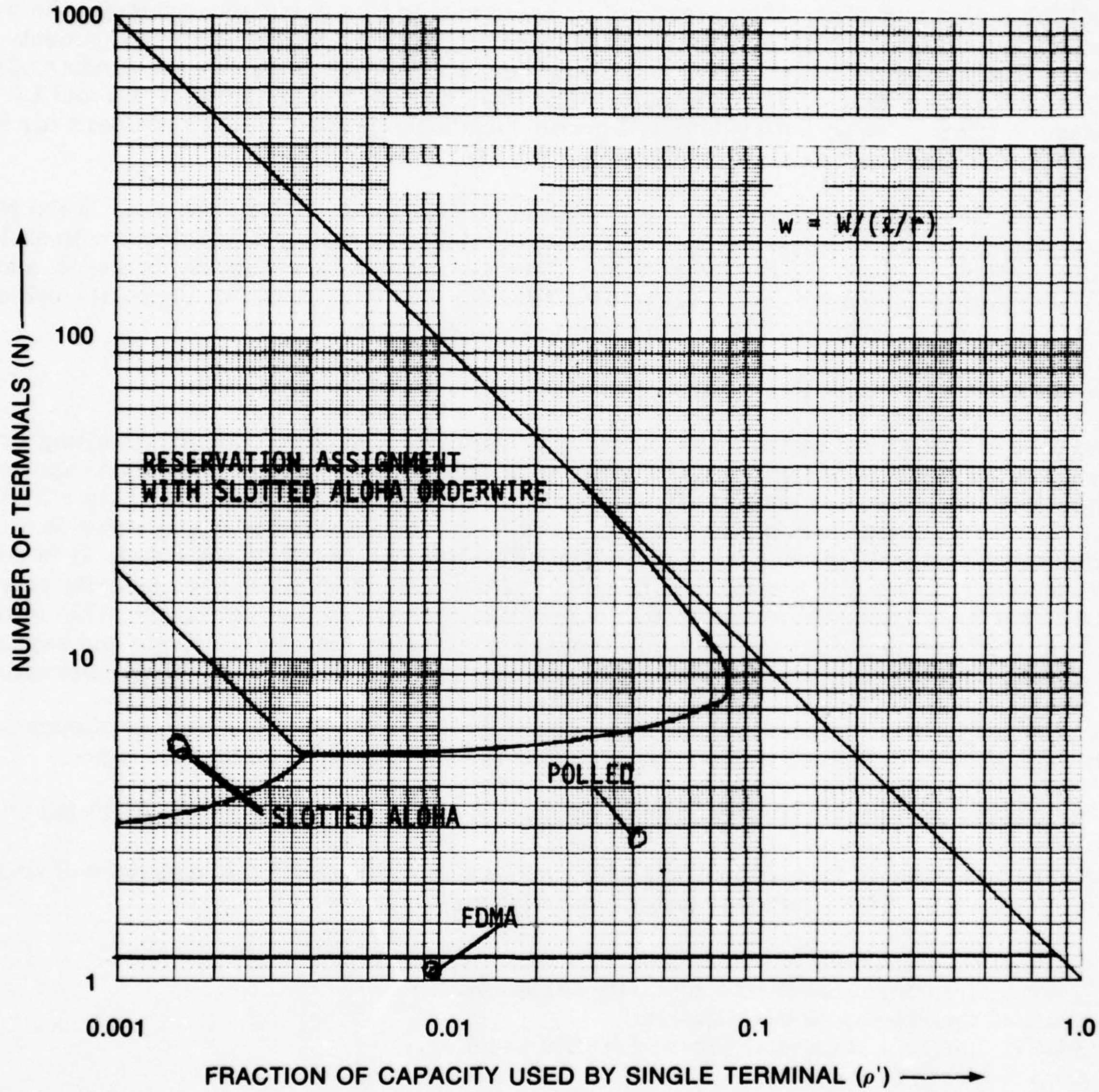


Figure 5-6. Areas in Which Each Type Access System Gives Minimum System Waiting Time for Random Length Messages with Random Arrivals. W = Normalized System Waiting Time in Message Lengths = $w/(\bar{\ell}/n)$.

the 24-hour mean traffic intensity (see reference 10 and appendix A). We shall assume that data traffic follows this same variation. Thus, the busy-hour traffic intensity for a terminal will be taken as 3 times the 24-hour mean traffic intensity for both voice and data. All terminals must be sized to handle this busy-hour traffic without exceeding the specified blocking probability for voice and without exceeding the maximum desired system waiting time for each priority of traffic by more than a specified fraction of the time for data.

In the case of BDA assignment systems, the satellite channels must also handle this busy-hour load while providing the specified grade of service.

For DAMA satellite systems, however, the network often spans several time zones. This case is analyzed in appendix A, where it is found that, for a uniform distribution of traffic over a 4-hour spread of time zones, the busy-hour traffic is only 2-1/2 times the 24-hour mean traffic. This reduces the busy-hour load on the satellite channels accordingly, and the number of satellite channels required to provide the specified grade of service are thereby reduced. This does not, however, reduce the busy-hour channel capacity or hardware required by a terminal.

As a result, for BDA systems, the terminal and satellite must be sized to handle a busy-hour traffic intensity which is 3 times the 24-hour average traffic intensity. However, for DAMA, the busy-hour traffic intensity at the satellite is reduced by a factor of 0.83.

5.3.2 Terminal-to-Terminal Traffic Intensity Variations

In the detailed analysis of a system, the terminal-to-terminal traffic intensity variations must be considered. In some cases the traffic model is detailed enough to show this variation, while in other cases the model only gives the total average traffic for a class of users. In the latter case we shall assume that the 24-hour mean traffic for terminals within a class varies from 0 to 2 times the mean for the class with a uniform distribution.

For BDA systems, the minimum number of channels required for a terminal is determined directly from the busy-hour traffic intensity for that terminal by use of figure 5-1. For DAMA systems, the minimum channel capacity and the corresponding minimum amount of hardware for a terminal is obtained directly from the BDA-reservation curve of figure 5-1. The minimum number of satellite channels required is obtained, however, by multiplying the sum of the busy-hour traffic intensities of all terminals within a community by the time spread factor (0.83) and using this as the input traffic intensity for figure 5-2.

5.3.3 Channel and Hardware Quantization

In many cases the number of voice channels used in a BDA or DAMA system are quantized. This quantization is done primarily for the purpose of hardware simplification. Also, in digital data systems, data rates have been standardized to be 75×2^n where n is an integer. Because of the channel and hardware quantizing, the final system will be somewhat overdesigned for the traffic. Assuming the required number of channels is uniformly logarithmically distributed* over the 2:1 quantizing interval, the number of channels and the

*If the logarithm of the number of channels is distributed uniformly over the quantizing interval, there will be no discontinuities in the distributions at the quantizing boundaries as there would be if a uniform distribution is assumed.

amount of hardware will be on the average 1.414 times more than the minimum required. However, because this factor may vary from 1 to 2, depending on the particular user and system model, the quantizing may distort the relative merits of the various assignment systems in some cases. We shall, therefore, not quantize the number of channels even though this may be done in a practical system.

5.3.4 Switched Versus Store-and-Forward Traffic Handling

In general, store-and-forward traffic handling cannot be used for full duplex voice communications because of the additional delay introduced. For data traffic, the utilization of the satellite channel capacity can often be increased by storing the message until the channel capacity for transmission is available. However, if the amount of data traffic is small compared to the amount of voice traffic, it may be economical to handle all data traffic as switched traffic. When data is handled as switched traffic, it will be assumed that the blocking probability for the data message shall not exceed 1 percent for all priority classes. This corresponds roughly to a 1-percent probability of exceeding the desired maximum system waiting time for an emergency class message.

5.3.5 Communication Security

There are two aspects of communications security that will be addressed. The first is message security and the second is traffic flow security. Message security involves denying the enemy knowledge of the contents of a message. Traffic flow security involves denying the enemy knowledge of the amount of traffic flowing, the routes of flow or command, and the message source and destination.

It is not our purpose to offer recommendations but only to alert the reader to potential system considerations.

5.3.5.1 Message Security

In order to maintain message security on radio links, it is necessary to encrypt transmissions. This can be accomplished either by encrypting and decrypting the message separately on each link (link encryption) or by encrypting the message at the source and decrypting the message at the final destination (end-to-end encryption). End-to-end encryption provides a higher degree of security than link encryption because the unencrypted message exists only at the source and the destination. However, the use of end-to-end encryption may preclude the use of time assignment speech interpolation (TASI) on voice links, since it may be impossible to determine when speech activity exists on the incoming line.

In order to decrypt messages at the receiving end of the link, the cryptographic sequence at the receiver must be in synchronism with the received message. The required cryptographic synchronization can be obtained either by transmitting a long cryptographic synchronization sequence as a preamble to a message or by maintaining time-to-day type synchronization. In general, cryptographic synchronization sequences are quite long and will appreciably increase the amount of time required to transmit the message. This is particularly true in the case of orderwire type traffic. Time-of-day type synchronization avoids the necessity of this long synchronization sequence. In time-of-day synchronization, the receiving and transmitting cryptographic sequences are kept in step by keeping the receiving and transmitting clocks in step at all times. It is generally impractical to maintain all clocks in perfect time step to the required accuracy. Even if this is done, the propagation delay must still be

accounted for. However, if time is quantized into message blocks, it is possible to decode a block if the block sequence number is known. If need be, the block sequence number can be transmitted as a part of the preamble, in the clear, since it tells an enemy no more than the time of day. Time-of-day cryptographic synchronization does not require any additional synchronization time above that normally required for bit sync and start-of-message sync for clear text messages. In all systems we have assumed that no special cryptographic synchronization preambles are required.

In some voice modulation systems, the carrier is turned off when there is no speech activity so as to conserve transmitter power. This will be referred to here as voice-operated transmit (VOX). VOX on a voice link may present a security problem in that there is a certain amount of information contained in the length and spacing of speech spurts which may compromise the security of the encrypted voice link.

5.3.5.2 Traffic Flow Security

In order to secure traffic flow from the enemy it is, of course, required to provide message security -- in particular, message header security, since this normally would identify the message source and destination. In addition, it is often required to secure the amount of traffic being transmitted from a given source. Traffic flow security is commonly maintained by transmitting random data when there is no message traffic present so that data is being transmitted continuously. Since the link is encrypted, it is impossible for the enemy to determine the amount of real message traffic being handled. Such a procedure precludes the use of demand assignment. If a demand-assignment system is used, the enemy can generally gain some knowledge of the amount of traffic flowing from a specific geographic location by monitoring emissions. Traffic flow security could perhaps be maintained by artificially generating a certain amount of random traffic so as to confuse enemy intelligence. The consideration of such systems is beyond the scope of this study. It will be assumed here that the required degree of message flow security can be obtained with demand-assignment systems by proper operational procedure. Such procedures may increase the amount of traffic capacity that a network must handle. It is assumed here, however, that procedures can be developed whereby this random cover traffic will not interfere with actual traffic so that all traffic analyses can be made without consideration of this additional random traffic.

5.3.6 Priority Protocol

In this study we assumed that priority protocol is provided for both voice and data. For voice, it is assumed that the priority protocol is provided by the end office or tandem switch which interfaces between the landlines and the satellite terminal. For voice traffic the satellite-terminal-to-satellite-terminal blocking probability for all traffic lumped together will be taken as 1 percent. DAMA systems will be sized to provide a 0.3-percent blocking probability within the end terminals and a 0.7 percent blocking probability with regard to satellite channel availability.

With Poisson arrivals and exponential holding times, there is no absolute upper limit on the waiting time in a store-and-forward traffic handling system. It is, therefore, impossible to guarantee that the maximum waiting times for a given priority class will never be exceeded. One can specify however that this maximum desired waiting time will not be exceeded more than a given percent of the time. We shall set 1 percent as the maximum probability that any given priority class message will have a waiting time greater than that specified. This situation is covered in paragraph 6 of appendix B.

Without priority discipline, all traffic must be handled with a maximum system waiting time for the highest priority message. From equation B-147 (of appendix B) we have the probability, P_1, that the system waiting time, W, will exceed the specified maximum system waiting time for priority 1 message, W_{m1}, given by

$$P_1 = P(w \geq W_{m1}) = \exp(-W_{m1}/\overline{W}), \tag{5-3}$$

where $\overline{W}$ is the mean system waiting time. Solving this for the maximum allowable mean system waiting time, $\overline{W}_m$, gives

$$\overline{W}_m = W_{m1}/\ell n(P_1) \tag{5-4}$$

Thus we must design a system where the mean system waiting time is less than or equal to $\overline{W}_m$.

With priority protocol, the higher priority messages are moved to the front of the queue. Within any given priority class, the messages are handled on a first-in, first-out basis. The minimum required message service time, μ_i, for the ith priority class of traffic is given by equation B-161 (of appendix B) as

$$\mu_i = \sum_{j=1}^{i=1} \lambda_i + \frac{1}{W_{mi}} \ell n \left[\frac{\lambda_i + (\exp(\lambda_i W_{mi}) - 1) \sum_{j=1}^{i} \lambda_j}{\lambda_i P_i} \right] \tag{5-5}$$

where λ_i is the message generation rate for the i^{th} priority class of traffic; W_{mi} is the maximum desired system waiting time for the i^{th} priority traffic; and P_i is the allowed probability of the system waiting time for the i^{th} traffic exceeding W_{mi}. The system must be designed to provide a message service rate which is equal to or greater than the largest of the μ_i's (μ_{max}). The minimum information bit rate, r_m, for the channel is

$$r_m = \overline{\ell} \mu_{max}, \tag{5-6}$$

where $\overline{\ell}$ is the mean message length in bits. The corresponding maximum mean system waiting time $\overline{W}_m$ is

$$\overline{W}_m = \frac{1}{\mu_{max} - \sum_{j=1}^{i_{max}} \lambda_j}. \tag{5-7}$$

When data is handled as switched traffic, there are two possible causes of message delays which may cause the system waiting time to exceed the desired maximum system waiting time. First, the switch may be blocked. This will not necessarily delay the message beyond the desired maximum system waiting time. Second, the message service time may exceed the desired system waiting time. The message service time, w', will be exponentially distributed with a mean of $\overline{\ell}/r$ where $\overline{\ell}$ is the mean message length in bits and r is the

bit rate of the channel. The probability that the message service time will exceed the desired system waiting time for priority class 1 messages is therefore given by

$$P(w' > W_{mi}) = \exp\left[(-W_{m1}/(\bar{\ell}/r)\right] \tag{5-8}$$

As an upper bound on the probability, P_{m1}, of exceeding the maximum desired system waiting time for priority class 1 messages, we have

$$P_{m1} \leq 1 - \left[1 - \exp\,(-W_{m1}/(\bar{\ell}/r))\right]\left[1 - P_b\right]$$

$$\approx = P_b + \exp\,(-W_{m1}/(\bar{\ell}/r)). \tag{5-9}$$

where P_b is the blocking probability.

5.3.7 Signaling for Control (Common Channel Versus In-Band Signaling)

Two methods of control signaling are commonly used for voice traffic. These are common channel signaling and in-band signaling. In common channel signaling, a separate channel is devoted to signaling for control. In in-band signaling, all control signaling required for a channel is transmitted over that channel. Exclusive use of in-band signaling would require every terminal to demultiplex and demodulate all channels of a network which might have traffic for it. In BDA-FDM systems, this would require a number of receiver demodulators. For this reason, common channel signaling will generally provide a much lower cost system. However, for a BDA system, when the number of transmitter channels per terminal is small, the addition of a channel exclusively devoted to the signaling function can appreciably increase the required satellite channel capacity. Common channel signaling is generally more economical except in the case of small BDA terminals, where in-band signaling is more economical.

5.3.8 Central Versus Distributed Control

For BDA and DAMA voice or data systems, central control is generally somewhat simpler and less prone to accidental disruption than distributed control. On the other hand, if the operation of the system is not to depend on the survivability of a single control node, provisions must be made so that another station can pick up the control function. The additional hardware, software, and protocol required will generally increase the complexity of the central control system to such a degree that there will be little or no cost savings in comparison to a distributed control system. Therefore, terminal cost is not a major discriminate between central and distributed control systems.

The successful operation of a distributed control system depends on every user maintaining the same list of current channel assignments and the same queuing list. Any error in correctly maintaining this list is a potential source of disruption of the system by incorrect terminal transmissions. Therefore great care must be exercised in maintaining the same channel assignment and queuing list at all terminals. This requires additional transmission of these lists for the purpose of confirmation of accuracy and error correction. Thus there will be some loss in traffic capacity due to the necessity of additional transmissions of the channel assignment and queuing lists. The data capacity of the central control system under normal operating condition will, therefore, be greater than that of a distributed control system.

5.4 REFERENCES

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In this section, the SHF candidate demand-assignment systems will be rated using the evaluation criteria developed in section 2 in conjunction with the SHF user models of section 4 and the analytic results of section 5. There are many system design parameters that affect the performance of a demand-assignment system. Such factors include priority, control, multiplexing, and multiple access.

As a result of these many factors, the number of detailed candidate systems that must be investigated is large. An analysis and evaluation of such a large number of detailed candidate systems is not possible within the scope of this study. The approach, therefore, will be to pare down the list of candidate DA systems by initial candidate selection based on simplified user models, system definitions, and simplified evaluation criteria. The only DA systems that will be eliminated in the initial selection are those which are obviously inferior to the retained candidates. This selection process will be repeated with more detail and realism included with each iteration.

6.1 INITIAL SHF CANDIDATE SELECTION

Examination of the SHF user models given in section 4 shows that the voice traffic is 97 percent of the total busy-hour traffic. Since voice traffic is so dominant, it is clear that these SHF systems should be designed first and foremost to handle voice traffic efficiently. The design for the handling of data traffic should then be done without introducing serious degradation of the voice traffic efficiency. We shall, therefore, consider only voice traffic in the initial candidate selection.

Both baseband demand assignment (BDA) and demand assignment multiple access (DAMA) systems will be considered for voice traffic. Three basic types of BDA systems will be considered. These systems are baseband demand assignment with reservation (BDA-reservation), baseband demand assignment with time assignment speech interpolation (BDA-TASI), and baseband demand assignment using slotted ALOHA random access (BDA-ALOHA).

Two basic types of DAMA systems will be considered. These systems are demand assignment multiple access with reservation (DAMA-reservation) and demand assignment multiple access using slotted ALOHA random access (DAMA-ALOHA). A subclass of DAMA-reservation which employs voice-operated transmitter activation (DAMA-VOX) will also be considered. This list includes the currently interesting generic types.

In comparing systems, we shall be interested in minimizing the total number of satellite channels required to handle the specified intensity of offered traffic. The satellite capacity can be measured either in terms of the required bandwidth or in terms of the required satellite power. The DA systems selected as initial candidates will be selected independent of whether bandwidth or power is used as the criterion in determining channel capacity. It is convenient to specify the bandwidth in terms of the number of equivalent voice channels.

All voice traffic is digital, using 16 kb/s CVSD modulation. The grade of service is specified in terms of the maximum allowable blocking probability and the minimum acceptable voice

quality imposed by the demand-assignment system. The maximum allowable blocking probability is 1 percent (reference 1), and minimum acceptable voice quality is reflected in the specified bit rate and in terms of the amount of speech sounds lost in TASI and ALOHA type systems due to contention. In keeping with current international standards and convention, the voice traffic will be treated as lost calls cleared (reference 1).

The mean holding time for a call for all user models is 3 minutes. This corresponds to 2.9 x 10^6 bits per call at 16 kb/s. Since only several-hundred bits of information are required to make a reservation, the control overhead for a call reservation is only 0.01 percent. The channel capacity required for the orderwire, therefore, is small and will be neglected in the initial candidate selection.

The type of multiplexing or multiple access used is not specified and is an engineering detail which will be considered later.

6.1.1 Application of BDA and DAMA to Simplified User Models

We shall now apply the analytic methods of section 5 and appendix A for BDA and DAMA systems to the shf user models developed in section 4. For simplicity, all terminals are assumed to have the same average busy-hour traffic intensity. For BDA systems, the number of baseband channels required per terminal can be read directly from figure 5-1. The total number of channels required is obtained by summing the number of channels required by the individual terminals. For DAMA systems, the total input traffic intensity is obtained by summing the input traffic intensity of the individual terminals. This total input traffic intensity is used with figure 5-2 to obtain the total number of satellite channels required.

6.1.2 FLTOPS Traffic

The total FLTOPS voice traffic is shown in table 6-1 along with the number of total channels required to handle this traffic for each of the candidate DA systems. For FLTOPS traffic, it is clear that DAMA-reservation and DAMA-VOX require less than half of the number of channels of any of the other systems. In addition, DAMA-VOX requires 4 dB less average satellite power than DAMA-reservation. For FLTOPS traffic, DAMA-reservation and DAMA-VOX are far superior to any of the other DA systems and therefore are chosen as the two initial candidates for this application.

Table 6-1. FLTOPS SHF Voice Demand-Assignment Techniques Comparison.

ITEM	VALUE
FLTOPS traffic	
Total busy-hour traffic intensity, *(A)	31.91 Erlangs
Total number of terminals in network, (N)	22
Busy-hour traffic intensity per terminal, (A')	1.45 Erlangs
BDA-reservation	
Baseband channels per terminal	6
Satellite channels required, (S)	132
BDA-reservation with TASI	
Baseband channels per terminal	5
Satellite channels required, (S)	110
BDA-ALOHA	
Baseband channels per terminal	16
Satellite channels required, (S)	352
DAMA-reservation and DAMA-VOX	
Satellite channels required, (S)	45
DAMA-ALOHA	
Satellite channels required, (S)	170
*See table 4-7.	

6.1.3 GMF Traffic

The results of applying the candidate DA systems to GMF traffic are shown in table 6-2. Here BDA-TASI requires the fewest number of channels to achieve the desired grade of service. However, DAMA-reservation and DAMA-VOX are very close and, therefore, must be retained as initial candidates. DAMA-VOX can provide the required communications with 4 dB less average satellite power than DAMA-reservation and with 2.6 dB less average satellite power than BDA-TASI.

Table 6-2. GMF SHF Voice Demand-Assignment Techniques Comparison.

ITEM	VALUE
GMF traffic	
Total busy-hour traffic intensity,* (A)	1532.1 Erlangs
Total number of terminals, (N)	60
Busy-hour traffic intensity per terminal (A')	25.5 Erlangs
BDA-reservation	
Baseband channels per terminal	36
Satellite channels required, (S)	2160
BDA-reservation with TASI	
Baseband channels per terminal	19
Satellite channels required, (S)	1140
BDA-ALOHA	
Baseband channels per terminal	130
Satellite channels required, (S)	7800
DAMA-reservation and DAMA-VOX	
Satellite channels required, (S)	1561
DAMA-ALOHA	
Satellite channels required, (S)	5620
*See table 4-8.	

6.1.4 DCS Traffic

The results of applying the candidate DA systems to DCS traffic are shown in table 6-3. For this traffic, BDA-TASI requires only 61 percent of the number of channels which would be required by DAMA-reservation or DAMA-VOX. However, because of the 4-dB savings in average power achieved by the application of VOX, DAMA-VOX would require 1.9 dB less average power than BDA-TASI. DAMA-reservation and DAMA-VOX systems also provide great flexibility in adapting to changes in traffic intensities at the individual terminals. For these reasons DAMA-reservation, DAMA-VOX, and BDA-TASI are all initial candidates for DCS traffic.

Table 6-3. DCS SHF Voice Demand-Assignment Techniques Comparison.

ITEM	VALUE
DCS traffic	
Total busy-hour traffic intensity,* (A)	861.01 Erlangs
Total number of terminals, (N)	21
Busy-hour traffic intensity per terminal, (A')	41 Erlangs
BDA-reservation	
Baseband channels per terminal	52
Satellite channels required, (S)	1092
BDA-reservation with TASI	
Baseband channels per terminal	26
Satellite channels required, (S)	546
BDA-ALOHA	
Baseband channels per terminal	195
Satellite channels required, (S)	4095
DAMA-reservation and DAMA-VOX	
Satellite channels required, (S)	890
DAMA-ALOHA	
Satellite channels required, (S)	3261

*See table 4-10.

6.1.5 SHF Initial Candidate Selection Summary

The SHF traffic for all three network models is predominantly voice traffic. For voice traffic, it was found that DAMA-reservation and DAMA-VOX perform well for all three user models considered and therefore are condidates for further study. DAMA-reservation and DAMA-VOX work efficiently for both small and large terminals. DAMA-VOX provides a power savings of 4 dB over a DAMA-reservation system. BDA-TASI provides high efficiency for the GMF and DCS, being more efficient than DAMA-VOX on the basis of satellite bandwidth requirements but less efficient than DAMA-VOX on a satellite power basis. DAMA-reservation and DAMA-VOX are the two initial candidate systems for FLTOPS. BDA-TASI is also retained as an initial candidate for GMF and DCS.

6.2 FINAL CANDIDATE SELECTION

In paragraph 6.1, an initial selection of SHF candidates was made on the basis of simplified modeling. Such simplifed selection procedures are valid provided that there are large differences in the performance of systems. However, a more detailed system definition and analysis is required in order to make choices between systems that provide nearly equal performance at nearly equivalent costs. In this section we shall define the user and the system in greater detail and will include such details as traffic variations between the terminals of a network, diurnal traffic variations, priority protocols, switched versus store-and forward data traffic handling, and network control traffic. The terminal-to-terminal traffic variations are given in section 4. The analysis of diurnal traffic variation, priority protocol, network control traffic, and switched versus store-and-forward data traffic handling are presented in section 5.

Using this data, a detailed analysis of the number of satellite channels required for each of the initial candidate demand-assignment systems will be made. Additionally, the probability of being able to get frequency assignments will be estimated for each candidate along with a determination of total system cost. The final selection process will identify those demand-assignment candidates that come closest to fulfilling the evaluation criteria, that is, require the fewest number of satellite channels, accommodate the lowest availability of frequency assignments, and have the lowest total system cost.

The demand-assignment candidates for detailed analysis are shown in table 6-4.

Table 6-4. SHF Demand-Assignment Candidates for Detailed Analysis.

DEMAND-ASSIGNMENT SYSTEM TYPE	DATA HANDLING	DATA PRIORITY PROTOCOL	MULTIPLEXING AND MULTIPLE ACCESS
BDA-reservation	Switched	No	TDM-TDMA TDM-FDMA FDM-FDMA
	Store-and-forward	No	TDM-TDMA TDM-FDMA FDM-FDMA
		Yes	TDM-TDMA TDM-FDMA FDM-FDMA
BDA-TASI	Switched	No	TDM-TDMA TDM-FDMA FDM-FDMA
DAMA-reservation	Switched	No	TDMA FDMA
	Store-and-forward	No	TDMA FDMA
		Yes	TDMA FDMA

6.2.1 Required Satellite Channel Capacity

In this section we will calculate the number of satellite channels required to support each of the SHF user models using each of the demand-assignment candidates of table 6-4. The multiplexing and multiple-access system used has no effect on the number of satellite channels required and is, therefore, not included in these considerations. The detailed traffic models for FLTOPS, GMF, and DCS are shown in tables 6-5, 6-6, and 6-7.

Table 6-5. FLTOPS Traffic.

TERMINAL NO	BUSY-HOUR TRAFFIC INTENSITY (Erlangs)			BUSY-HOUR CALLING RATE (calls/second)		
	VOICE	DATA	TOTAL	VOICE	DATA	TOTAL
1	0.05	0.001	0.051	0.0003	0.0003	0.0006
2	0.05	0.001	0.051	0.0003	0.0003	0.0006
3	0.11	0.003	0.113	0.0006	0.0006	0.0012
4	0.26	0.007	0.267	0.0014	0.0014	0.0028
5	0.36	0.010	0.370	0.0020	0.0020	0.0040
6	0.36	0.010	0.370	0.0020	0.0020	0.0040
7	0.41	0.011	0.421	0.0023	0.0023	0.0046
8	0.72	0.020	0.740	0.0040	0.0040	0.0080
9	0.72	0.020	0.740	0.0040	0.0040	0.0080
10	0.77	0.021	0.791	0.0043	0.0043	0.0086
11	0.87	0.024	0.894	0.0048	0.0048	0.0096
12	0.87	0.024	0.894	0.0048	0.0048	0.0096
13	1.00	0.027	1.027	0.0056	0.0056	0.0112
14	1.18	0.033	1.213	0.0066	0.0066	0.0132
15	1.18	0.033	1.213	0.0066	0.0066	0.0132
16	1.29	0.036	1.326	0.0072	0.0072	0.0144
17	1.72	0.048	1.768	0.0096	0.0096	0.0192
18	2.18	0.061	2.241	0.0121	0.0121	0.0242
19	3.26	0.091	3.351	0.0181	0.0181	0.0362
20	3.34	0.093	3.433	0.0186	0.0186	0.0372
21	5.38	0.149	5.529	0.0299	0.0299	0.0598
22	5.83	0.162	5.992	0.0324	0.0324	0.0648
Totals	31.91	0.885	32.795	0.1775	0.1775	0.3550

DATA PRIORITY		
PRIORITY CLASS	TOTAL TRAFFIC (%)	MAXIMUM SYSTEM WAITING TIME (seconds)
Y	0.02	30
Z	0.08	60
O	5.00	300
P	42.00	3,600
R	52.90	10,800
Total	100.00	

DATA
Bit rate = 2,400 b/s Mean message length = 12,000 bits Holding time = 5 seconds
VOICE
Bit rate = 16 kb/s CVSD Holding time = 180 seconds

Table 6-6. GMF Traffic.

TERMINAL NO	BUSY-HOUR TRAFFIC INTENSITY (Erlangs)			BUSY-HOUR CALLING RATE (calls/second)		
	VOICE	DATA	TOTAL	VOICE	DATA	TOTAL
1	2.57	0.07	2.64	0.014	0.064	0.078
2	2.87	0.08	2.95	0.016	0.073	0.089
3	9.21	0.25	9.46	0.052	0.229	0.281
4	13.77	0.37	14.14	0.078	0.339	0.417
5	14.18	0.38	14.56	0.080	0.349	0.429
6	14.32	0.39	14.71	0.081	0.358	0.439
7	16.24	0.44	16.68	0.091	0.404	0.495
8	17.30	0.47	17.77	0.097	0.431	0.528
9	18.24	0.49	18.73	0.103	0.450	0.553
10	18.67	0.50	19.17	0.105	0.459	0.564
11	18.79	0.51	19.30	0.106	0.468	0.574
12	19.73	0.53	20.26	0.111	0.486	0.597
13	20.46	0.55	21.01	0.115	0.505	0.620
14	23.82	0.64	24.46	0.134	0.587	0.721
15	24.29	0.66	24.95	0.137	0.606	0.743
16	27.36	0.74	28.10	0.154	0.679	0.833
17	35.37	0.96	36.33	0.199	0.881	1.080
18	50.29	1.36	51.65	0.283	1.248	1.531
19	60.94	1.65	62.59	0.343	1.514	1.857
20	102.28	2.76	105.04	0.576	2.532	3.108
Totals	510.70	13.80	524.50	2.875	12.662	15.537
	x 3*	x 3*	x 3*	x 3*	x 3*	x 3*
Total Network	1532.10	41.40	1573.50	9.625	37.986	46.611

*Total network is composed of three identical 20-terminal Army Corps.

DATA PRIORITY		
PRIORITY CLASS	TOTAL TRAFFIC (%)	MAXIMUM SYSTEM WAITING TIME (seconds)
Y	0.05	30
Z	0.2	60
O	2.5	300
P	22.25	3,600
R	75.00	10,800
Total	100.00	

DATA
Bit rate = 2,400 b/s Mean message length = 2,616 bits Holding time = 1.09 seconds
VOICE
Bit rate = 16 kb/s CVSD Holding time = 177.6 seconds

Table 6-7. DCS Traffic.

TERMINAL NO	BUSY-HOUR TRAFFIC INTENSITY (Erlangs)			BUSY-HOUR CALLING RATE (calls/second)		
	VOICE	DATA	TOTAL	VOICE	DATA	TOTAL
1	4.13	0.115	4.24	0.023	0.023	0.046
2	4.13	0.115	4.24	0.023	0.023	0.046
3	5.16	0.143	5.30	0.029	0.029	0.058
4	12.39	0.344	12.73	0.069	0.069	0.138
5	12.39	0.344	12.73	0.069	0.069	0.138
6	12.39	0.344	12.73	0.069	0.069	0.138
7	12.39	0.344	12.73	0.069	0.069	0.138
8	21.68	0.602	22.28	0.120	0.120	0.240
9	24.78	0.688	25.47	0.138	0.138	0.276
10	24.78	0.688	25.47	0.138	0.138	0.276
11	27.87	0.774	28.65	0.155	0.155	0.310
12	37.17	1.033	38.20	0.207	0.207	0.414
13	37.17	1.033	38.20	0.207	0.207	0.414
14	37.17	1.033	38.20	0.207	0.207	0.414
15	37.17	1.033	38.20	0.207	0.207	0.414
16	49.55	1.376	50.93	0.275	0.275	0.550
17	49.55	1.376	50.93	0.275	0.275	0.550
18	74.33	2.065	76.40	0.413	0.413	0.826
19	78.46	2.179	80.64	0.436	0.436	0.872
20	123.88	3.441	127.32	0.688	0.688	1.376
21	174.47	4.846	179.32	0.969	0.969	1.938
Totals	861.01	23.916	884.91	4.786	4.786	9.572

DATA PRIORITY		
PRIORITY CLASS	TOTAL TRAFFIC (%)	MAXIMUM SYSTEM WAITING TIME (seconds)
Y	0.02	30
Z	0.08	60
O	5.00	300
P	42.00	3,600
R	52.90	10,800
Total	100.00	

DATA
Bit rate = 2,400 b/s Mean message length = 12,000 bits Holding time = 5 seconds
VOICE
Bit rate = 16 kb/s CVSD Holding time = 180 seconds

6.2.1.1 Method of Calculation of Channel Requirements

The SHF satellite communication systems must be sized so as to handle all the voice, data, and control traffic with the required grade of service. All voice traffic is full duplex, 16-kb/s digital voice. The voice communication system must be sized so as to provide a system blocking probability of 1 percent or less. (See reference 1.)

All input data traffic is at 2,400 b/s. The data communication system must be sized so that the probability of exceeding the maximum desired system waiting time for any priority class of traffic (as given in tables 6-5 through 6-7) is 1 percent or less. If no priority protocol system is employed, all data traffic must be handled as the highest priority of traffic in order to guarantee that the system waiting time for the highest priority traffic will not be exceeded more than 1 percent of the time. When data traffic is handled as switched traffic, a maximum blocking probability of 1 percent will be used. The time required to establish a switch connection will not be included in the system waiting time. This approach gives a slightly undersized system. However, since the control circuit is designed for an average system waiting time of only 1 second for the control message, the total system waiting time for control plus the traffic will be increased by only a few seconds.

All control traffic operates at 2,400 b/s. Except for TASI, the control messages are assumed to be 240 bits long. It is assumed that two control messages are required to establish a store-and-forward connection and that the maximum mean waiting time for a control message shall not exceed 1 second.

For TASI, it is assumed that one 2,400-b/s circuit will be assigned to handle the TASI control for up to 25 voice channels.

6.2.1.1.1 Switched Traffic System Sizing

A switched call on a satellite communications link, whether voice or data, can be blocked because of either a lack of idle satellite channels or a lack of terminal hardware. The total blocking probability for voice traffic is to be 1 percent. This must be proportioned between satellite channel blocking probability and the terminal equipment blocking probability. In the case of BDA, there is a one-to-one correspondence between satellite channels and terminal modulators so that the blocking probability for the satellite channel and the terminal modulator hardware will be set at 1 percent for sizing. In the case of DAMA, the system will be designed to provide 0.7-percent blocking probability due to the lack of satellite channels and a 0.3-percent blocking probability of a terminal, so as to provide an overall blocking probability of 1.0 percent.

In all cases, sizing will be done for a lost-calls-cleared system to conform with CCITT standards (reference 1). Sizing is therefore done, using the Erlang B equation. A complete set of tables for system sizing using the Erlang B equation is provided in Siemens' traffic tables (reference 2).

In the case of TASI, the number of baseband channels required will be calculated as described in appendix A, paragraph 2. These results are shown in figure A-3.

If data is handled as switched traffic, the terminal input traffic in Erlangs is the total busy-hour traffic intensity, which is the sum of the busy-hour <u>voice</u> traffic intensity and the busy-hour <u>data</u> traffic intensity. If data is handled as store-and-forward traffic, only the busy-hour <u>voice</u> traffic should be included in the input traffic in sizing the <u>switch traffic</u> channels.

In the case of DAMA, the traffic originates from a number of local time zones. This tends to smooth the peak traffic on the satellite channel. This is discussed in appendix A. For a 4-hour spread in time zones, which we shall assume, the busy-hour traffic intensity or the satellite channels loading is reduced by the factor, 0.833. Thus for DAMA systems, the satellite channel capacity should be designed for a busy-hour input traffic of 0.833 times the sum of the terminal busy-hour input traffic intensity. The terminal hardware must, of course, be designed to handle the total busy-hour traffic intensity for that terminal since the individual terminal traffic is not smoothed by the spread in network time zones.

6.2.1.1.2 Store-and-Forward Traffic System Sizing

For store-and-forward data traffic handling, we shall assume that all data is transmitted on a single high-speed data channel and that the data traffic has a Poisson message arrival distribution and an exponential message length distribution. We shall further assume that any control required is provided on a separate control channel and that the time required to place the reservation is not included in the system waiting time. Under these conditions, the data channel becomes an ideal M/M/1 queuing system as described in appendix B. The minimum acceptable message service rate is calculated for each priority class using equation B-161 (appendix B) and the largest of these, μ_{max}, is used in equation B-162 to calculate the minimum acceptable bit rate for the store-and-forward data traffic. The minimum number of channels required to provide this bit rate is calculated assuming 2,400-b/s capacity per voice circuit.

6.2.1.1.3 Control Channel Sizing

The control channel is sized so that the mean system waiting time is 1 second or less. The control channel must provide the capacity to handle both voice and data reservations. The reservation messages are assumed to be 240 bits long, and the control channel is assumed to operate at 2,400 b/s times the number of circuits devoted to control. It is assumed that two control messages are required for every reservation of a switched connection and that one control message is required for every store-and-forward message. For a BDA system, this corresponds to the ideal M/G/1 queuing system for fixed message length. The mean system waiting time, W, is given by

$$W = \frac{1}{2}\frac{\ell}{r}\left(\frac{2 - \lambda \ell/r}{1 - \lambda \ell/r}\right) \qquad (6\text{-}1)$$

where ℓ is the control message length (240 bits), r is the control channel bit rate and λ is the total calling or message generation rate. Solving equation 6-1 for λ gives

$$\lambda = \frac{1}{\ell/r}\,\frac{2W/(\ell/r) - 2}{2W/(\ell/r) - 1} \qquad (6\text{-}2)$$

For our case, W is 1 second minus the propagation delay of 0.25 second, or 0.75 second, and λ is 9.29 messages or calls per second. Since no FLTOPS, GMF, or DCS single-terminal calling rate exceeds 3.1 calls per second, not more than one reservation channel will be required for any BDA system. In the case of a BDA system with only a few channels, the addition of a reservation control channel would increase the number of channels required by an appreciable amount. Therefore, for four or fewer BDA satellite channels, in-band signaling will be used instead of common channel signaling.

For BDA-TASI, the TASI control channel must also be provided for the dynamic reassignment of circuits. One 2,400-b/s control channel is added for every 25 TASI traffic channels for this function in accordance with normal TASI practices.

For DAMA-reservation, a single high-speed data channel will be provided for all control and reservation traffic. For this purpose a slotted ALOHA system will be used. This system for fixed length messages with random arrivals is covered in appendix B. The mean system waiting time, W, is given by equation B-83 (appendix B) as:

$$W = \begin{cases} \dfrac{\ell}{r}\left\{\dfrac{\Delta}{(\ell/r)} + 1 + 4\left(\dfrac{\Delta}{\ell/r} + 8\right)(\lambda\ell/r)^{3/2}\right\} & \text{for } \lambda\,\ell/r < 0.35 \\ \infty & \text{for } \lambda\,\ell/r \geq 0.35 \end{cases} \qquad (6\text{-}3)$$

where Δ is the satellite round-trip propagation delay. In practice, $\lambda\,\ell/r$ should not exceed 0.2. Even with only a 2,400-b/s control line, W is 0.73 second for $\lambda\,\ell/r = 0.2$, so that in practice, the control channel requirements are dictated by channel instability rather than by waiting time. Thus the governing condition is $\lambda\,\ell/r \leq 0.2$ and we have

$$r_{\text{DAMA control}} \geq 5\lambda\ell \qquad (6\text{-}4)$$

In some cases the required number of control channels could be reduced by using fixed-assignment TDMA for the control traffic. However, the savings is always small compared to the total voice traffic capacity of the system and would not change the relative standings of the demand-assignment systems being considered.

6.2.1.2 Sizing of Detailed Candidate Systems

Each of the seven candidate demand-assignment systems has been sized for each of the three SHF user models in accordance with the procedures specified in the previous paragraphs. The overall results are presented in table 6-8. The calculations leading up to these results are shown in tables 6-9 through 6-14.

Table 6-8. SHF System Comparison.

DA SYSTEM TYPE	NUMBER OF EQUIVALENT VOICE CIRCUITS REQUIRED		
	FLTOPS	GMF	DCS
BDA-reservation			
All switched	133	2,304	1,176
Store-and-forward data			
With priority	152	2,328	1,205
Without priority	152	2,316	1,193
BDA-TASI			
All switched	122	1,302	622
DAMA			
All switched	41	1,388	784
Store-and-forward data			
With priority	42	1,388	785
Without priority	41	1,388	784

Table 6-9. FLTOPS BDA System Satellite Channel Requirements.

TERM NO	BDA-RESERVATION											BDA-TASI		
	SWITCHED WITHOUT PRIORITY			STORE-AND-FORWARD WITHOUT PRIORITY				STORE-AND-FORWARD WITH PRIORITY				SWITCHED WITHOUT PRIORITY		
	VOICE + DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE CIRCUITS	DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE CIRCUITS	DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE + DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS
1	2	0	2	2	1	0	3	2	1	0	3	2	0	2
2	2	0	2	2	1	0	3	2	1	0	3	2	0	2
3	2	0	2	2	1	0	3	2	1	0	3	2	0	2
4	3	0	3	3	1	0	4	3	1	0	4	3	0	3
5	3	0	3	3	1	0	4	3	1	0	4	3	0	3
6	3	0	3	3	1	0	4	3	1	0	4	3	0	3
7	4	0	4	4	1	0	5	4	1	0	5	4	0	4
8	4	0	4	4	1	0	5	4	1	0	5	4	0	4
9	4	0	4	4	1	0	5	4	1	0	5	4	0	4
10	5	1	6	4	1	0	5	4	1	0	5	5	1	6
11	5	1	6	5	1	1	7	5	1	1	7	5	1	6
12	5	1	6	5	1	1	7	5	1	1	7	5	1	6
13	5	1	6	5	1	1	7	5	1	1	7	5	1	6
14	5	1	6	5	1	1	7	5	1	1	7	5	1	6
15	5	1	6	5	1	1	7	5	1	1	7	5	1	6
16	6	1	7	6	1	1	8	6	1	1	8	6	1	7
17	7	1	8	6	1	1	8	6	1	1	8	7	1	8
18	7	1	8	7	1	1	9	7	1	1	9	7	1	8
19	9	1	10	9	1	1	11	9	1	1	11	6	1	7
20	9	1	10	9	1	1	11	9	1	1	11	6	1	7
21	12	1	13	12	1	1	14	12	1	1	14	8	1	9
22	13	1	14	13	1	1	15	13	1	1	15	8	1	9
Total	120	13	133	118	22	12	152	118	22	12	152	105	13	122

Table 6-10. FLTOPS DAMA System Satellite Channel Requirements.

DAMA SYSTEM TYPE	NUMBER OF EQUIVALENT VOICE CHANNELS			
	SWITCHED CIRCUITS	STORE-AND-FORWARD CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS
Switched data Without priority	40	0	1	41
Store-and-forward data Without priority	39	2	1	42
With priority	39	1	1	41

Table 6-11. GMF BDA System Satellite Channel Requirements.

TERM NO	BDA-RESERVATION											BDA-TASI		
	SWITCHED WITHOUT PRIORITY			STORE-AND-FORWARD WITHOUT PRIORITY				STORE-AND-FORWARD WITH PRIORITY				SWITCHED WITHOUT PRIORITY		
	VOICE + DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE CIRCUITS	DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE CIRCUITS	DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE + DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS
1	8	1	9	8	1	1	10	8	1	1	10	6	2	8
2	9	1	10	8	1	1	10	8	1	1	10	6	2	8
3	18	1	19	17	1	1	19	17	1	1	19	11	2	13
4	24	1	25	23	1	1	25	23	1	1	25	14	2	16
5	24	1	25	24	1	1	26	24	1	1	26	14	2	16
6	24	1	25	24	1	1	26	24	1	1	26	14	2	16
7	27	1	28	26	1	1	28	26	1	1	28	15	2	17
8	28	1	29	28	1	1	30	28	1	1	30	15	2	17
9	29	1	30	29	1	1	31	29	1	1	31	16	2	18
10	30	1	31	29	1	1	31	29	1	1	31	16	2	18
11	30	1	31	29	1	1	31	29	1	1	31	16	2	18
12	31	1	32	31	1	1	33	31	1	1	33	17	2	19
13	32	1	33	31	1	1	33	31	1	1	33	17	2	19
14	36	1	37	35	1	1	37	35	1	1	37	19	2	21
15	37	1	38	36	1	1	38	36	1	1	38	20	2	22
16	40	1	41	40	1	1	42	40	1	1	42	21	2	23
17	50	1	51	49	2	1	52	49	1	1	51	25	2	27
18	67	1	68	65	2	1	68	65	1	1	67	33	3	36
19	79	1	80	77	2	1	80	77	1	1	79	38	3	41
20	125	1	126	122	3	1	126	122	2	1	125	57	4	61
Total	748	20	768	731	25	20	776	731	21	20	772	390	44	434
* (times 3)	2,244	60	2,304	2,193	75	60	2,328	2,193	63	60	2,316	1,170	132	1,302

* Total network is composed of three identical systems.

Table 6-12. GMF DAMA System Satellite Channel Requirements.

DAMA SYSTEM TYPE	NUMBER OF EQUIVALENT VOICE CHANNELS			
	SWITCHED CIRCUITS	STORE-AND-FORWARD CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS
Switched data Without priority	1,350	0	38	1,388
Store-and-forward data Without priority	1,315	35	38	1,388
With priority	1,315	35	38	1,388

Table 6-13. DCS BDA System Satellite Channel Requirements.

TERM NO	BDA-RESERVATION											BDA-TASI		
	SWITCHED WITHOUT PRIORITY			STORE-AND-FORWARD WITHOUT PRIORITY				STORE-AND-FORWARD WITH PRIORITY				SWITCHED WITHOUT PRIORITY		
	VOICE + DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE CIRCUITS	DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE CIRCUITS	DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS	VOICE + DATA CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS
1	11	1	12	11	1	1	13	11	1	1	13	7	2	9
2	11	1	12	11	1	1	13	11	1	1	13	7	2	9
3	12	1	13	12	1	1	14	12	1	1	14	8	2	10
4	22	1	23	22	2	1	25	22	1	1	24	13	2	15
5	22	1	23	22	2	1	25	22	1	1	24	13	2	15
6	22	1	23	22	2	1	25	22	1	1	24	13	2	15
7	22	1	23	22	2	1	25	22	1	1	24	13	2	15
8	34	1	35	33	2	1	36	33	1	1	35	18	2	20
9	37	1	38	37	2	1	40	37	1	1	39	20	2	22
10	37	1	38	37	2	1	40	37	1	1	39	20	2	22
11	41	1	42	40	2	1	43	40	1	1	42	21	2	23
12	52	1	53	51	2	1	54	51	2	1	54	26	3	29
13	52	1	53	51	2	1	54	51	2	1	54	26	3	29
14	52	1	53	51	2	1	54	51	2	1	54	26	3	29
15	52	1	53	51	2	1	54	51	2	1	54	26	3	29
16	66	1	67	65	3	1	69	65	2	1	68	32	3	35
17	66	1	67	65	3	1	69	65	2	1	68	32	3	35
18	94	1	95	92	3	1	96	92	3	1	96	44	3	47
19	99	1	100	96	3	1	100	96	3	1	100	46	3	49
20	148	1	149	145	5	1	151	145	4	1	150	67	4	71
21	203	1	204	198	6	1	205	198	5	1	204	89	5	94
Total	1,155	21	1,176	1,134	50	21	1,205	1,134	38	21	1.193	567	55	622

Table 6-14. DCS DAMA System Satellite Channel Requirements.

DAMA SYSTEM TYPE	NUMBER OF EQUIVALENT VOICE CHANNELS			
	SWITCHED CIRCUITS	STORE-AND-FORWARD CIRCUITS	CONTROL CIRCUITS	TOTAL CIRCUITS
Switched data Without priority	776	0	8	784
Store-and-forward data Without priority	756	21	8	785
With priority	756	20	8	785

Inspection of table 6-8 will reveal the following:

a. The use of store-and-forward data handling never reduces the number of satellite channels required. This is because the effect is small and because the addition of special channels exclusively for data actually increases the number of channels required.
b. The use of priority protocol does not reduce the number of satellite channels appreciably. This is because the effect of priority protocol is small.

Since cost and complexity are increased by use of priority protocol and store-and-forward data handling and there is no corresponding decrease in the number of satellite channels required, it is clear that these techniques should not be chosen as the final candidate for any user models. These results stem basically from the fact that the data traffic is such a small fraction of the total traffic.

For FLTOPS traffic, a DAMA-reservation system requires the fewest number of satellite channels. This is primarily due to the fact that FLTOPS is composed of a large number of very low traffic users. There is little difference in the number of satellite channels required by a BDA-reservation system and a BDA-TASI system. This is because few terminals have enough traffic to make TASI pay. It appears that for FLTOPS, DAMA-reservation would be the best system. However, because of the fact that the cost of BDA systems may be lower than DAMA systems, BDA-reservation, BDA-TASI, and DAMA-reservation (with or without VOX) will be carried on through the costing part of this study.

For GMF and DCS traffic, BDA-TASI requires about 50 percent of the channels required for BDA-reservation and about the same number of channels required by DAMA-reservation. DAMA-VOX, however, will provide a 4-dB power saving over DAMA-reservation without VOX so that DAMA-VOX will require about 4.0 dB less average satellite power than BDA-TASI. Because the cost of some of these systems may offset their inefficient use of satellite channels, BDA-reservation, BDA-TASI, and DAMA-reservation (with or without VOX) will be carried on through the costing part of this study.

6.2.2 Frequency-Assignment-Availability Requirements

The frequency-management evaluation criterion used in evaluating the DA candidates is defined in section 2 as the frequency-assignment-availability requirement,

F = the fraction of the frequency assignments comprising a specified bandwidth that must be available for assignment, so that the probability of obtaining the number of assignments needed by the DA candidate to serve the user model traffic is 0.5.

For the SHF models considered, the total bandwidth is assumed to be 185 MHz, the (narrow-beam to narrow-beam antennas) DSCS II transponder bandwidth. For the 16-kb/s rate and 1.125 bandwidth-to-transmission-rate ratio utilized for SHF QPSK modulation, the equivalent bandwidth per voice band channel is 18 kHz. In general, the bandwidth available for use at an earth terminal will appear in "segments" corresponding to the terrestrial radio-relay allotment plan used in the area. Seven MHz is a fairly common allotment size in effect in the European area. Thus, the 185-MHz transponder bandwidth can be considered as comprising 26 assignments of 7-MHz bandwidth, with each assignment including 388 voice channels. This amounts to a total of 10,088 voice channels, each occupying 18 kHz. As an intermediate point of reference, a 1-MHz bandwidth assignment includes 55 voice channels.

The probability of obtaining assignments for the capacity needed to serve a given traffic level using any TDMA candidate is a function of the contiguous assignment bandwidth required. For the purpose of demonstrating the effect of assignment bandwidth on the

frequency-assignment-availability requirement for TDMA, the following have been considered: 7-MHz, 1-MHz, and 18-kHz assignments. The relationship observed in the derivations and computations is that the value of F increases with decreasing assignment bandwidth for the TDMA candidates. Only the results for 7-MHz assignments are presented here.

Figures 6-1, 6-2, and 6-3 present the results of applying the equations from table 2-1 to the SHF FLTOPS, GMF, and DCS user models, respectively. Shown in each figure is the satellite network traffic capacity as a function of the terrestrial-system spectrum usage satisfying the 0.5 probability of successful assignments, for the user model parameters listed in table 4-11. The several curves are for the following DA candidates, for the frequency assignment parameters listed in table 6-15: DAMA-FDMA; BDA-FDMA; BDA-TASI-FDMA; and DAMA-TDMA, for assignment bandwidths of 7 MHz, 1 MHz, and 18 KHz. The same probability values associated with obtaining a given number of assignments, using the equations of table 2-1, are applicable to DAMA-TDMA, BDA-TDMA, and BDA-TASI-TDMA candidates. Only the amount of traffic served per quantity of satellite channel capacity is variable among the candidates. Also, the curves representing BDA-FDMA and BDA-TASI-FDMA are equally applicable to candidates using either TDM or FDM baseband multiplexing techniques, that is, the analysis is not affected by the multiplexing technique, assuming equal multiplex efficiencies. The results for FDMA systems are not significantly dependent upon the assignment bandwidth considered; the values shown in these figures are calculated for 26 total assignments of 7 MHz each. In all cases, values are computed for an integer number of assignments and smooth curves are drawn between points.

Curves are shown both for the "transmit-assignment only" case and the "receive- and transmit-assignments" case. The multiple-access efficiencies for DAMA-TDMA and DAMA-FDMA are assumed to be equal. It is of interest to note that for the satellite network traffic level corresponding to one assignment the allowable terrestrial-system usage is the same for the DAMA-TDMA and DAMA-FDMA candidates, for each of the 3 assignment increments considered. This is valid because, with only one assignment needed, the contiguous assignment requirement for TDMA has no impact on the availability. Values for less than 1 integral assignment have not been considered for TDMA.

Also shown in each figure is the network traffic level for the applicable user model. The intersection of this line with the DA candidate system curve defines, for each, the maximum allowable fraction of assignments in-use, q. From this amount the frequency-assignment-availability requirement, F, is calculated by

$$F = 1 - q. \qquad (6-5)$$

The resultant values for F are listed in table 6-16 for the four DA candidates applied to the SHF user models. The notable differences are that the availability requirement for DAMA-TDMA equals or exceeds that for other DA candidates. In particular, where only transmit assignments and not receive protection (assignments) are needed, the availability requirement for BDA systems is significantly less than for DAMA systems. Except for user models with a very low traffic intensity per terminal, the BDA-TASI system is superior to the BDA system, from frequency-management considerations.

It should be noted that the Erlang axis of each figure (6-1, 6-2, 6-3) is also representative of the efficiency of satellite bandwidth resource utilization, as shown on the right-hand ordinate axis. For each candidate, 100 percent utilization efficiency is taken as corresponding to the traffic level served by the DA system using the full 185-MHz transponder bandwidth without spectrum availability restrictions. The appropriate right-hand axis is used with the candidate curve to determine the potential utilization efficiency for a specific fraction of assignments in use. The results for the typical value of q = 5 percent are shown in

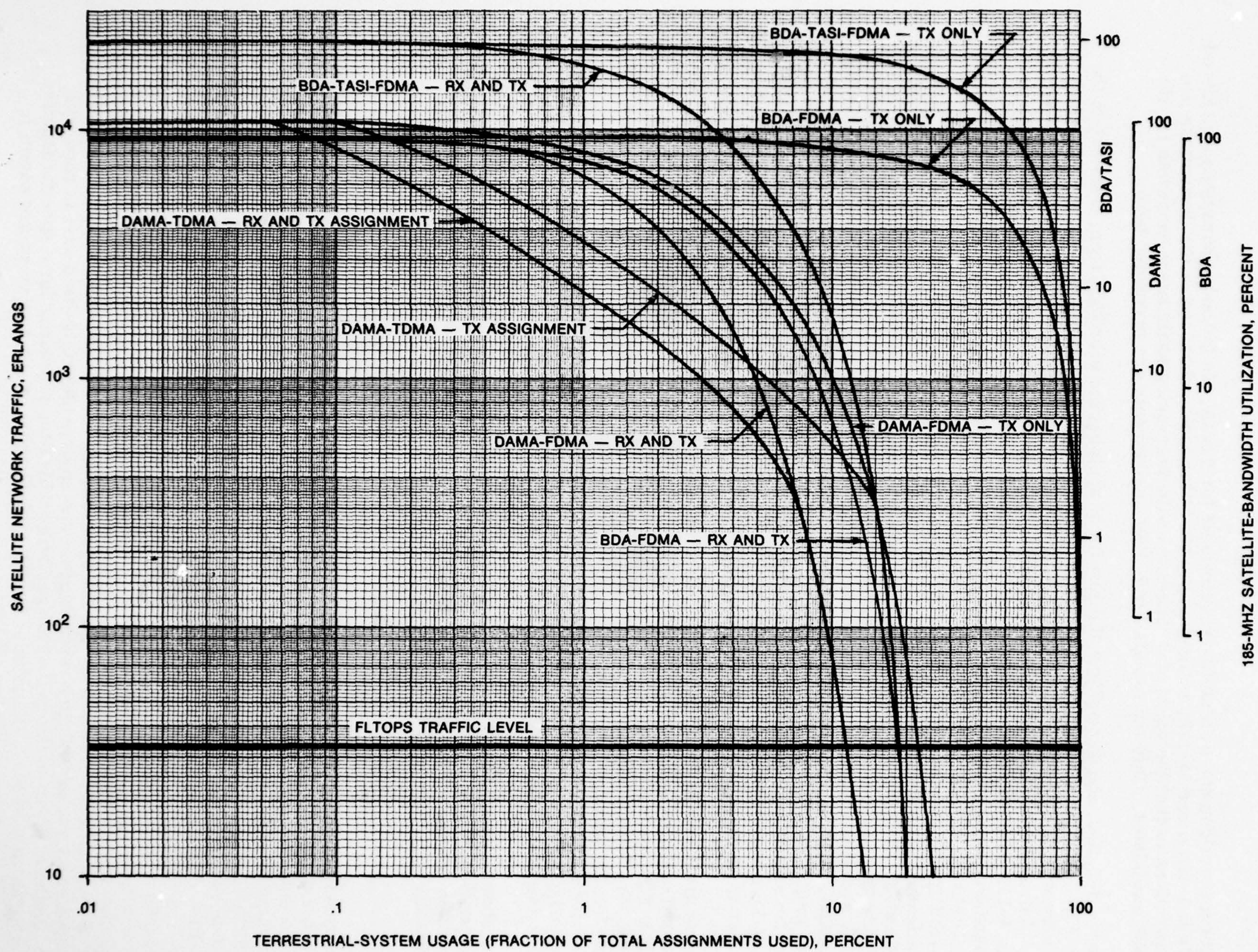

Figure 6-1. SHF Network Traffic Versus Terrestrial Usage for 22 Earth Terminals (FLTOPS).

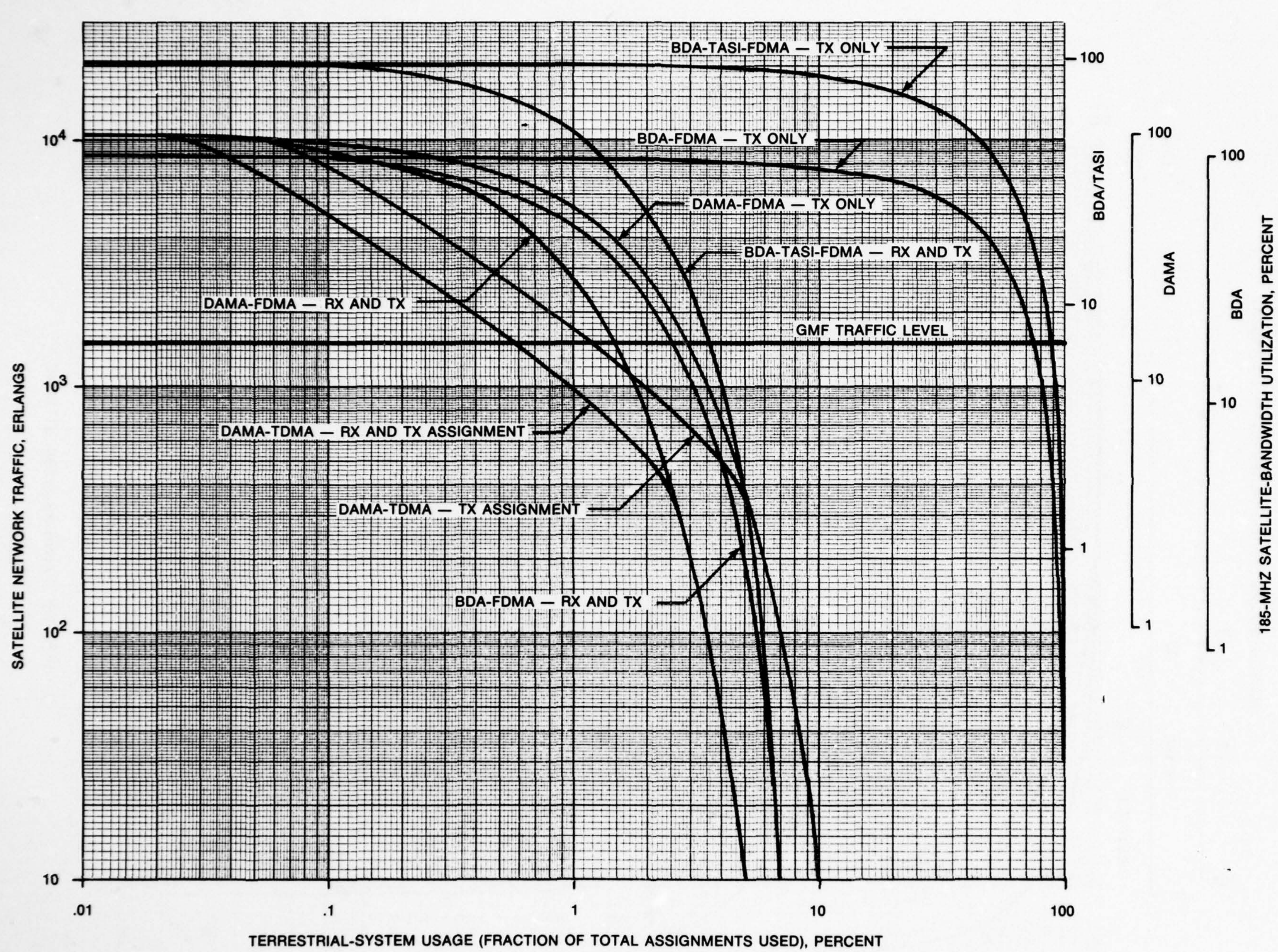

Figure 6-2. SHF Network Traffic Versus Terrestrial Usage for 60 Earth Terminals (GMF).

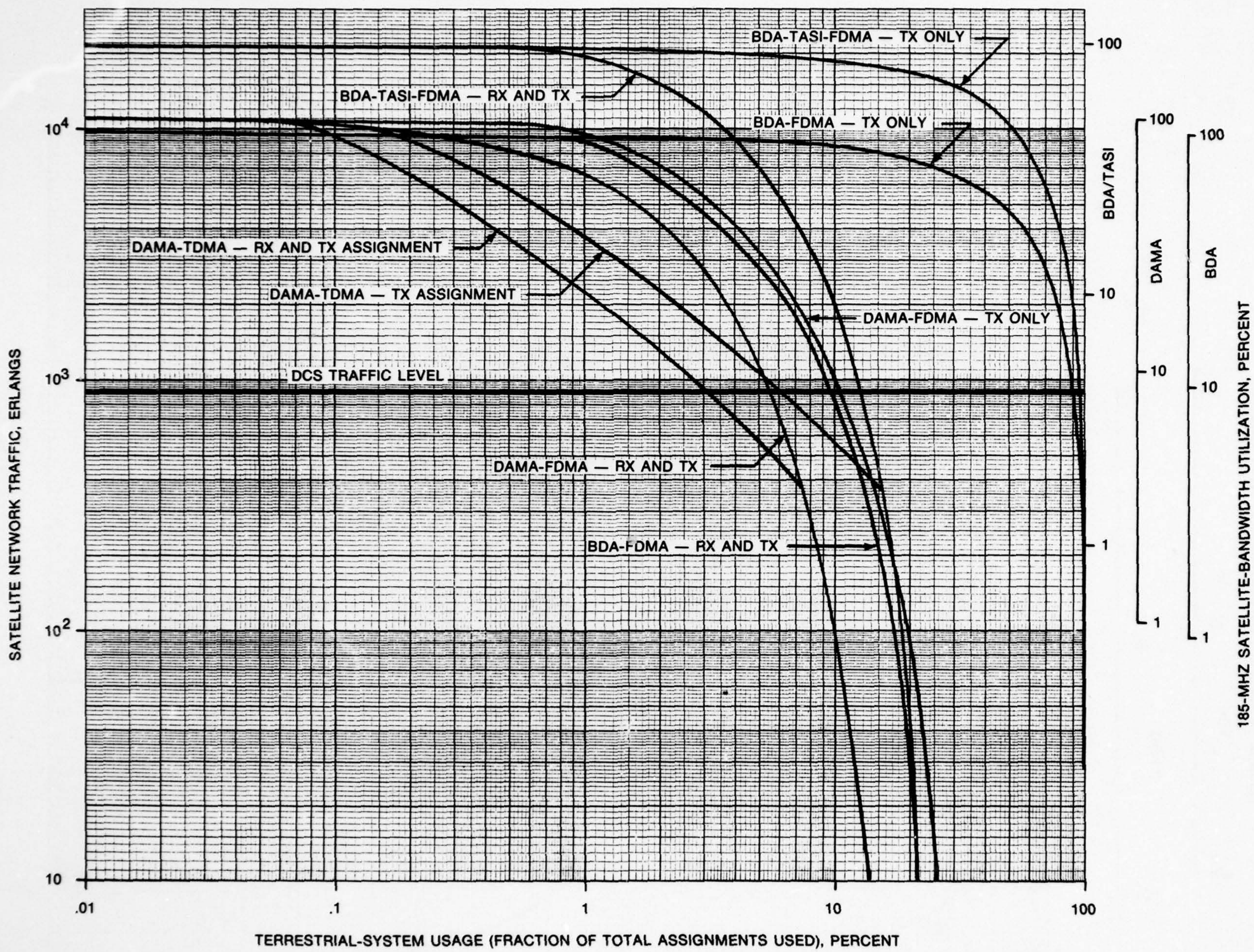

Figure 6-3. SHF Network Traffic Versus Terrestrial Usage for 21 Earth Terminals (DCS).

Table 6-15. Parameters.

a.	Satellite transponder bandwidth = 185 MHz
b.	Assignment bandwidth = 7 MHz
c.	Voice channel bandwidth ≃ 18 kHz
d.	Voice channels per satellite transponder = 10,088
e.	Uniform traffic level at all terminals is assumed
f.	The allowable degree of terrestrial-system usage of the total assignments is computed for 50-percent probability of obtaining the number of spectral assignments required to support the network traffic level indicated by the curves for the DA candidate systems for parameters listed in section 5.
g.	The equations for each candidate are found in the corresponding entry in table 2-1.

Table 6-16. Required Fraction of Frequency Assignments Available, F.
(For user model traffic level and terminal quantity, considering 185-MHz satellite transponder bandwidth. For 50 percent probability of obtaining all required assignments.)

DA CANDIDATE	FLTOPS		GMF		DCS	
	RX & TX	TX ONLY	RX & TX	TX ONLY	RX & TX	TX ONLY
DAMA-TDMA (7-MHz assignments)	0.890	0.780	0.994	0.988	0.967	0.939
DAMA-FDMA	0.890	0.780	0.985	0.970	0.945	0.897
*BDA-FDMA	0.820	0.010	0.974	0.250	0.903	0.120
*BDA-TASI-FDMA	0.810	0.010	0.965	0.110	0.875	0.050
**BDA-TDMA	0.890	0.780	0.996	0.992	0.976	0.952
**BDA-TASI-TDMA	0.890	0.780	0.991	0.984	0.952	0.897

*The baseband multiplex technique does not affect analysis. The results hold equally well for BDA TDM-FDMA and BDA FDM-FDMA.

**Data for these candidates was calculated but not presented in figures 6-1, 6-2, and 6-3.

table 6-17 and again demonstrate the higher ranking of BDA systems over DAMA candidates, from frequency management considerations.

Table 6-17. Potential Satellite-Bandwidth Utilization, Percent

(For 5-percent terrestrial-system usage of 185-MHz bandwidth spectrum)

DA CANDIDATE	22 TERMINALS (FLTOPS)		60 TERMINALS (GMF)		21 TERMINALS (DCS)	
	RX & TX	TX ONLY	RX & TX	TX ONLY	RX & TX	TX ONLY
DAMA-TDMA (7-MHz assignments)	5.5	10	0.1	3.5	5.1	9.8
DAMA-FDMA	9	29	0.1	3.5	10	29
*BDA-FDMA	28	98	2.2	96	29	92
*BDA-TASI-FDMA	28	90	1.6	92	30	93

*The baseband multiplex technique does not affect analysis. The results hold equally well for BDA TDM-FDMA and BDA FDM-FDMA.

6.2.3 SHF DA System Cost

One of the important criteria for evaluating the different candidate demand-assignment techniques is the total system cost. The approach of this section will be to present each technique with an explanation of its block diagram and cost summary. The actual cost analysis will be conducted in appendix C. The following candidates will be analyzed for total system cost:

a. Baseband Demand Assignment; Baseband Multiplex Technique: TDM; Multiple Access Technique: TDMA (BDA TDM-TDMA).
b. Baseband Demand Assignment; Baseband Multiplex Technique: TDM; Multiple Access Technique: FDMA (BDA TDM-FDMA).
c. Baseband Demand Assignment; Baseband Multiplex Technique: FDM; Multiple Access Technique: FDMA (BDA FDM-FDMA).
d. Demand Assignment Multiple Access; TDMA (DAMA-TDMA).
e. Demand Assignment Multiple Access; FDMA (DAMA-FDMA).

The cost developed in this report does not constitute a formal cost presentation. Rather it is a rough order of magnitude cost which is intended to provide a reasonable basis for

cost comparison of each demand assignment candidate. No other use or application of these costs is intended nor should any be inferred.

6.2.3.1 BDA TDM-TDMA

This BDA technique uses time-division multiplexing at baseband and a time-division multiple-access technique for its satellite link. The assignment at baseband is implemented by switched data traffic where common channel signaling is used. Two distinctive systems are considered, systems with TASI and systems without TASI. Each of the SHF models will be costed individually.

Figure 6-4 shows a typical block diagram of a BDA TDM-TDMA system. It is assumed that the baseband interface will be with a device similar to the TTC-39 digital switch. The input will be 16 kb/s channels of continuously variable slope delta modulated data appearing in the form of a TDM data stream.

The system will take the CVSD data, TTY data channels, and control channels and multiplex them into a single data channel. A variation of this system would include a TASI processor that would dynamically reassign channels during any change of its channel busy status. The TDM unit also contains protocol and channel reassignment circuitry that operates in

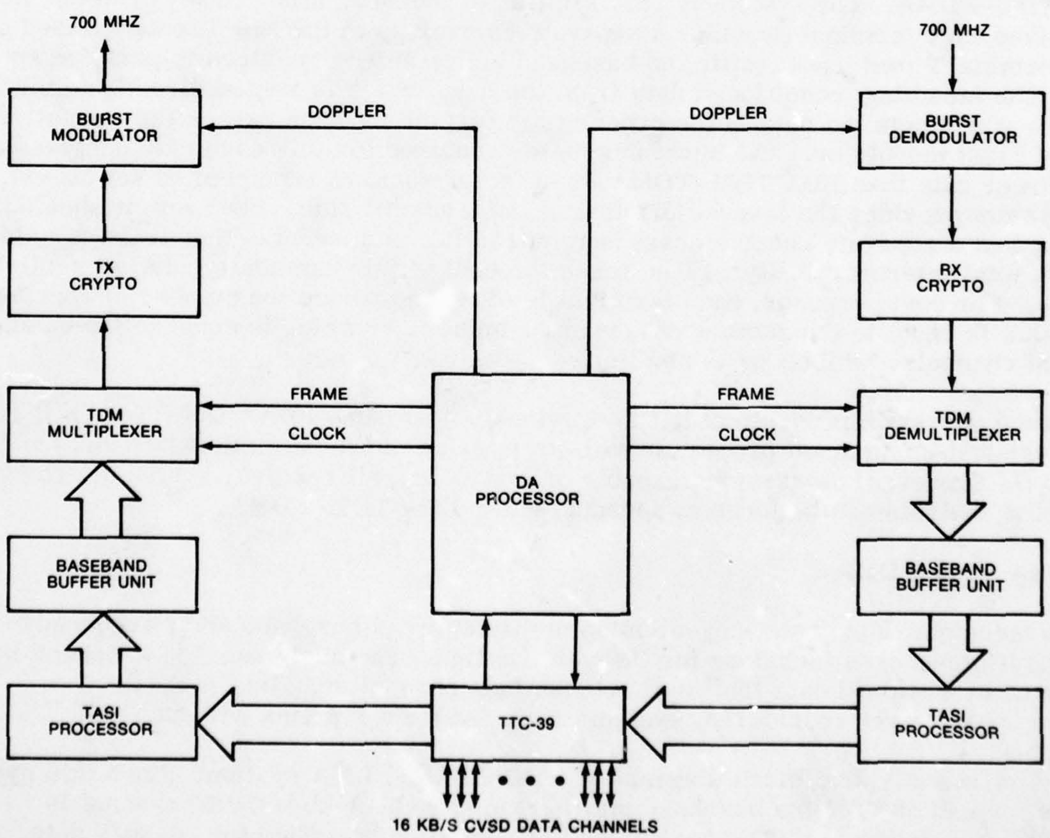

Figure 6-4. BDA TDM-TDMA.

conjunction with the system demand assignment processor. The processor controls and coordinates the assignment of all the available channels. It also provides proper coordination with destination processors both for message routing and timing.

Incoming data is conditioned by the GFE data switch. From the data switch it goes to a baseband buffer unit that provides storage for incoming data to accommodate the difference between the data rate and transmission burst rate. From there the data is sent to the TDM multiplexer, which assembles the data and then sends it to the burst modulator at the proper time. The TDM multiplexer controls all transmit side timing.

The satellite link for the TDMA system is a large TDM loop where each terminal has a fixed amount of permanently assigned capacity. The single channel data stream can be encrypted before the modulation process. However, it would be necessary to encrypt data at a 5- to 50-Mb/s data rate. Another optional requirement is the need for a high-power transmitter and/or a high-gain antenna. The TDMA loop requires a system capable of large EIRP values. The receive section of this candidate is just the reverse process of the transmit section. It should be noted that only one receiver is needed to receive all net members. The detailed cost analysis for this candidate is located in appendix C.

6.2.3.2 BDA TDM-FDMA

This BDA technique uses time-division multiplexing at baseband and a frequency-division multiple-access technique for its satellite link. Figure 6-5 shows a typical block diagram for BDA TDM-FDMA. The system is very similar to the BDA TDM-TDMA system. However, because each terminal provides a separate carrier up to the satellite comprised of only the terminal's own input traffic, no baseband buffer unit is required to perform speed changes. The incoming, conditioned data from the data switch is routed directly to the TDM multiplexer which puts the data in the proper time format and then passes the formatted data to the burst modulator. The burst modulator required for this candidate operates at a much slower rate than BDA TDM-TDMA (by a factor equal to 1/number of net users). The receive system provides the inverse function of the transmit side. However, it should be pointed out that a separate receive chain is required for each receive link at the terminal. Therefore, total interoperability will increase the cost of this candidate relative to all TDMA candidates. For cost purposes, each terminal is sized to provide the number of receive channels that is equal to the number of network members or which is equal to the number of terminal channels, whichever is smaller.

The baseband operation is identical to the previously described BDA TDM-TDMA. It contains the demand-assignment processor with its interface to the digital switch and the TDM unit. One DA processor is assumed capable of controlling all receiver systems. The detailed cost analysis can be found in appendix C for BDA TDM-FDMA.

6.2.3.3 BDA FDM-FDMA

This BDA technique uses frequency-division multiplexing at baseband and a frequency-division multiple-access technique for its satellite link. The assignment at baseband is implemented by switched data traffic where common channel signaling is used. Two distinctive systems are considered, systems with TASI and systems without TASI.

Figure 6-6 shows a typical block diagram of a BDA FDM-FDMA system. Since this system uses FDM instead of TDM for baseband multiplexing, each 16-kb/s CVSD channel is assigned its own rf carrier. The encryption units must be specified for 16-kb/s data. The demand assignment processor is required for message protocol and routing, but is not needed for link timing and synchronization because FDMA is used. It has nodal control

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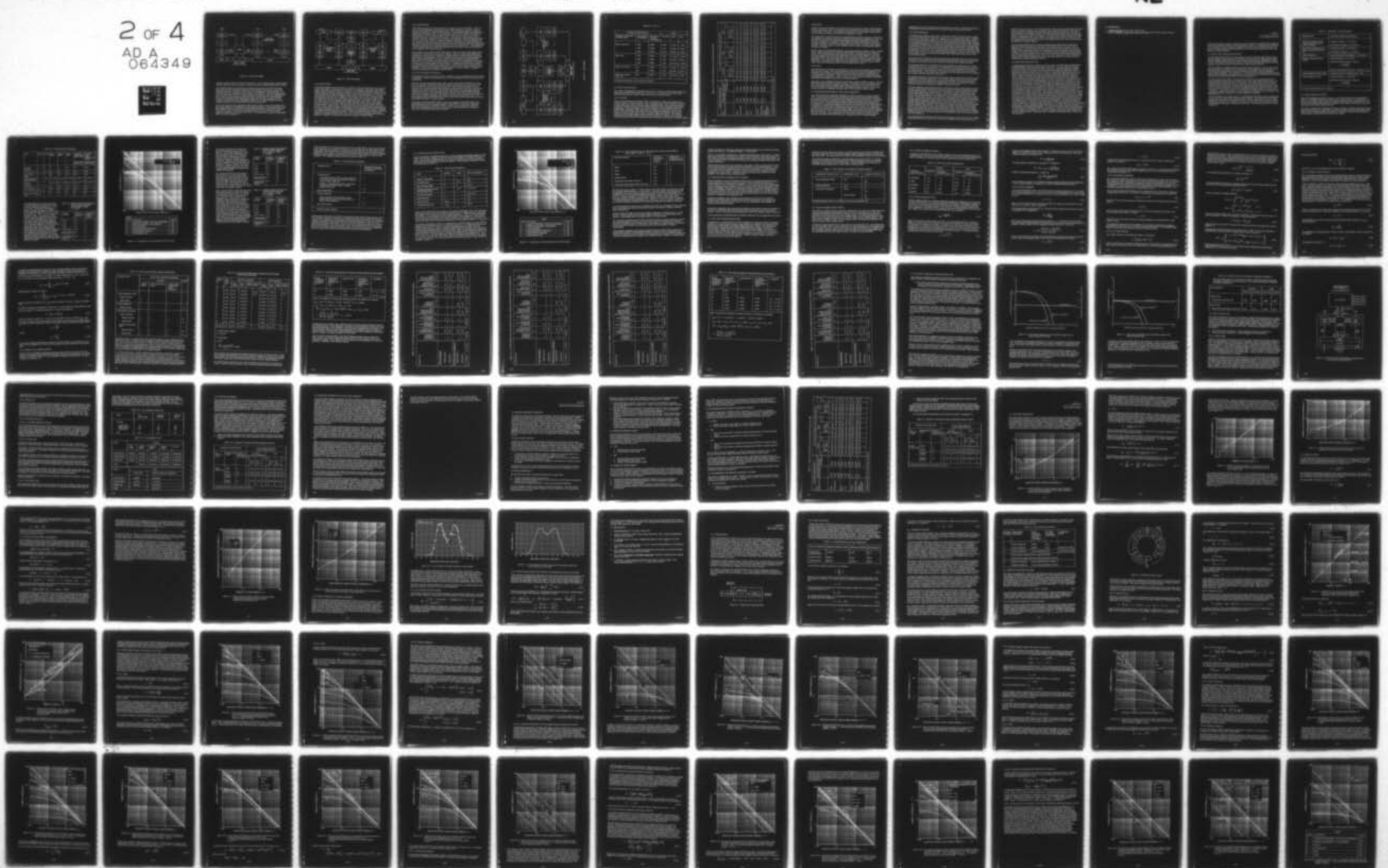

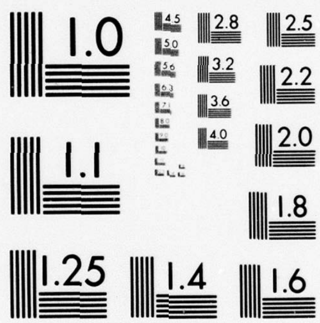

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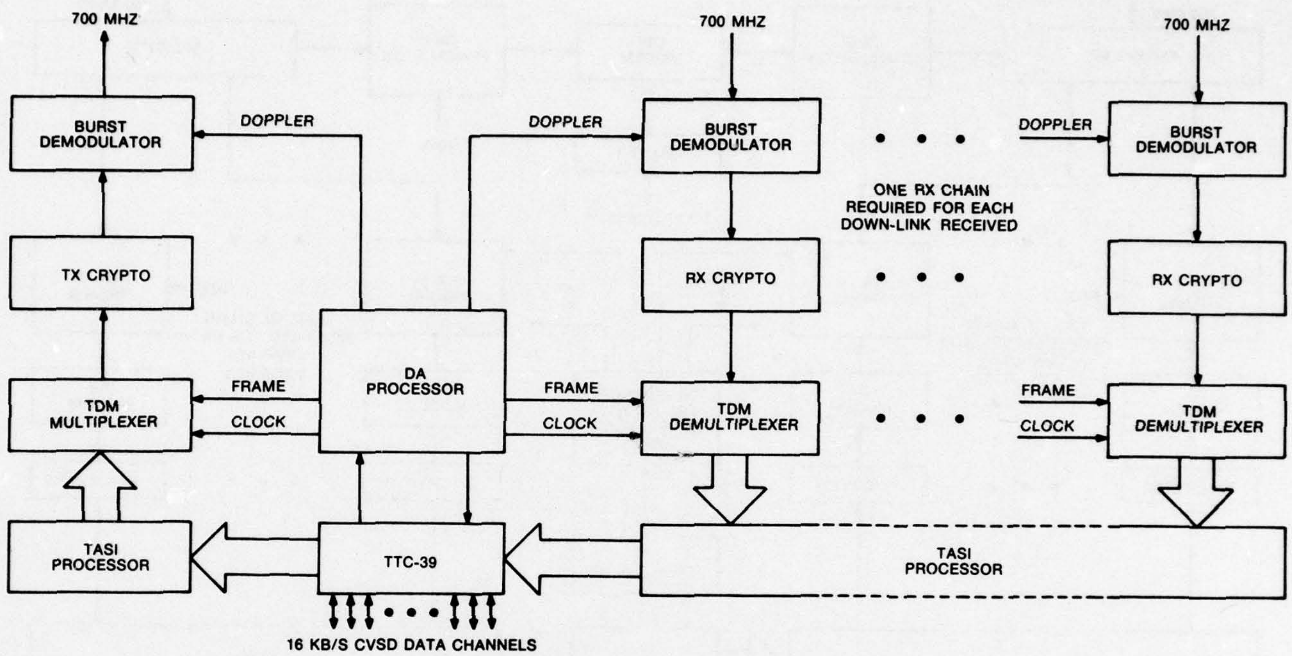


Figure 6-5. BDA TDM-FDMA.

through a control channel with other DA processors. By use of this common control channel between terminals, the DA processor can direct and receive traffic labeled with its address.

The baseband interface is assumed to be a digital switch similar to the TTC-39 whose input will be 16-kb/s channels of CVSD data. Each channel is routed into a modem that changes the data into a nominal 70-MHz carrier. This signal for each channel goes to a translator that has a synthesized local oscillator controlled by a reference frequency generator. It converts the carrier to a nominal frequency of 700 MHz. The exact frequency for each channel is under processor control and can be located anywhere in the SHF band. However, the definition of BDA FDM-FDMA implies that the fixed-assigned rf uplink carriers of each terminal lie in contiguous rf channels. The separate carriers are then combined and passed on to the SHF upconverter for transmission.

The receive system is the complement of the transmit section. Each receive channel has to have the capability to tune anywhere in the assigned SHF band. This requires that a 700-MHz splitter be used in conjunction with individual if translators to provide the signal to each receive modem. One reference frequency generator can provide all necessary translation frequencies for transmit and receive. The detailed cost analysis for BDA FDM-FDMA is located in appendix C.

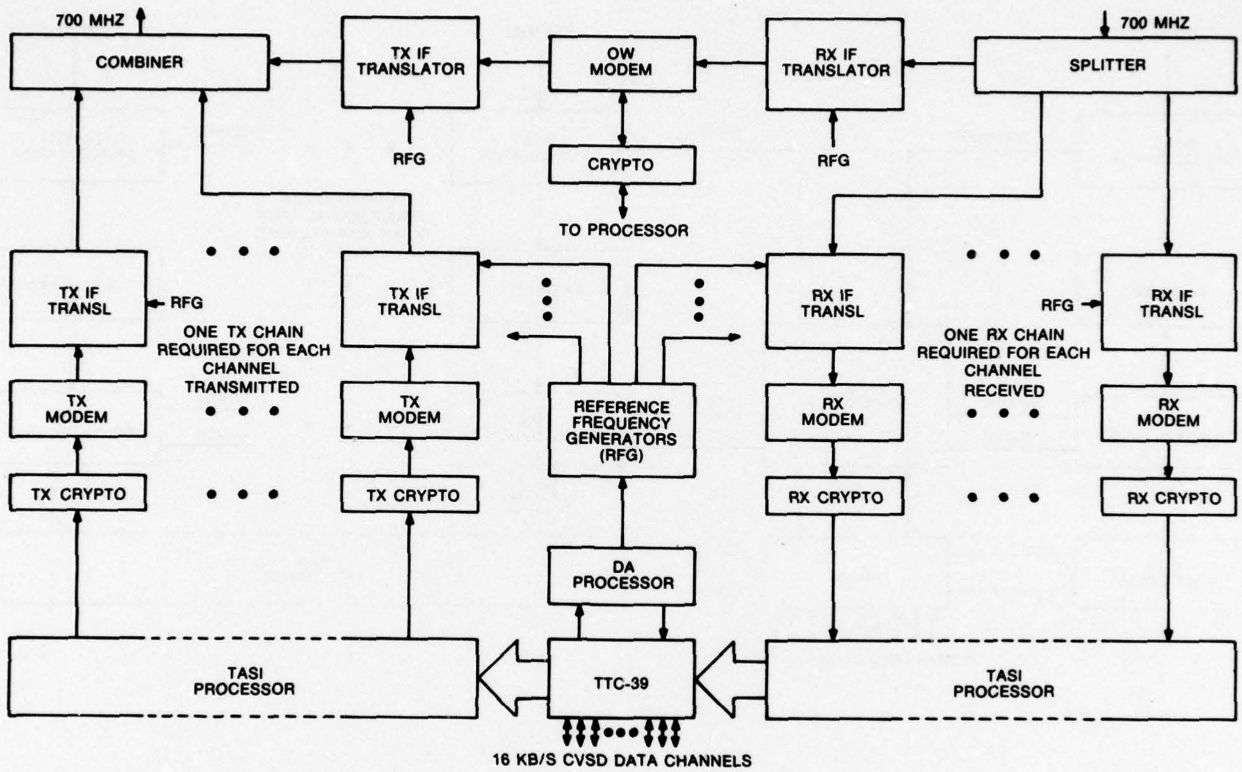


Figure 6-6. BDA FDM-FDMA.

6.2.3.4 DAMA-TDMA

This DAMA technique uses time-division to multiple access the satellite and is very similar to BDA TDM-TDMA. The difference between the two candidates is that BDA TDM-TDMA assigns on demand the fixed terminal rf capacity to its individual subscribers where DAMA-TDMA assigns the satellite capacity on demand to any terminal subscriber requiring service. The block diagram for either candidate is the same and is shown in figure 6-4. The baseband interface is assumed to be a digital switch similar to the TTC-39. The inputs from each subscriber will be 16 kb/s CVSD data. Each channel flows through the digital switch to a buffer unit where the necessary speed changing occurs. From there the data is sent to the TDM unit for time formatting into a single high-speed data stream. Then, when capacity is assigned to the user by the processor, the data is sent to the burst modulator for transmission to the satellite. The burst modulator must be capable of data rates up to 50 mb/s. DAMA-TDMA requires a large EIRP to provide the high-speed data transmissions. The demand assignment processor is responsible for the sequencing of the 16-kb/s channels on the high-speed data loop and the correct routing of the demultiplexed channels. Encryption is possible at the high-speed data interface. The GFE-supplied encryption unit must be capable of operation at the burst rate. The receive side is the complement of the transmit equipment. Appendix C contains the detailed cost analysis for DAMA-TDMA.

6.2.3.5 DAMA-FDMA

This DAMA technique uses frequency-division multiple access to the satellite. The VOX option is costed separately for each of the user models considered. Figure 6-7 shows a typical block diagram of a DAMA-FDMA system. The baseband interface is assumed to be a digital switch similar to the TTC-39 whose input will be 16-kb/s channels of CVSD data. Each channel is routed through an optional VOX processor into a modem. The modem changes the data into a nominal 70-MHz carrier. This signal for each channel goes to a translator that has a synthesized local oscillator controlled by a reference frequency generator. It converts the carrier to a nominal frequency of 700 MHz. The exact frequency for each channel is under processor control and can be located anywhere in the SHF band. The separate carriers are then combined and passed on to the SHF up-converter for transmission. Encryption is possible for each channel before the data is converted to rf. The specification of the encryption unit must include the capability for 16-kb/s data. The receive system is the complement of the transmit section.

DAMA-FDMA is very similar to BDA FDM-FDMA in that each 16-kb/s data channel forms a separate rf carrier both to and from the satellite. However, in BDA FDM-FDMA each terminal has a fixed amount of contiguous rf channels that are shared among the terminals subscribers on a demand basis. The rf relationship (frequency) of the up-link channels is fixed. DAMA-FDMA differs in that the rf capacity of the satellite is shared among all subscribers of all terminals on a demand basis. Further, the rf relationship of the up-link channels at any terminal changes from assignment to assignment and, therefore, requires a more capable up-link frequency translator system. The receive section of each candidate is identical because the rf frequency relationship of the down-link channels depends on call destination. Each candidate requires the same number of receive channels. Appendix C contains the detailed cost analysis for DAMA-FDMA.

6.2.3.6 SHF Candidate Cost Summary

The production cost for each of the SHF DA candidates listed in paragraph 6.2.3 is determined in appendix C. Table 6-18 summarizes the cost of each candidate for each of the three user communities.

Table 6-18 reveals that for BDA, either with or without TASI, BDA TDM-TDMA is always the least expensive candidate with BDA FDM-FDMA costing from 40 to 250 percent more with TASI and from 55 to 615 percent more without TASI. BDA TDM-FDMA is at least 35 percent more costly than BDA FDM-FDMA for systems without TASI and at least 89 percent more for systems with TASI. Clearly BDA TDM-FDMA is the most expensive BDA candidate and is not a serious candidate for final selection. BDA FDM-FDMA, although always more expensive than BDA TDM-TDMA, is fairly close for FLTOPS which represents a user with low traffic requirements and cannot be eliminated on the basis of cost. With the exception of BDA TDM-TDMA, BDA-TASI is always less expensive than BDA-reservation and should be included as a final candidate.

For DAMA reservation, DAMA-TDMA is always less expensive than DAMA-FDMA with DAMA-FDMA using VOX being slightly higher. When DAMA is compared to BDA using identical multiple access techniques, DAMA is between 1 to 8 percent more expensive. Cost will be a significant factor in the choice between TDMA and FDMA but will play no major role in choosing between DAMA and BDA.

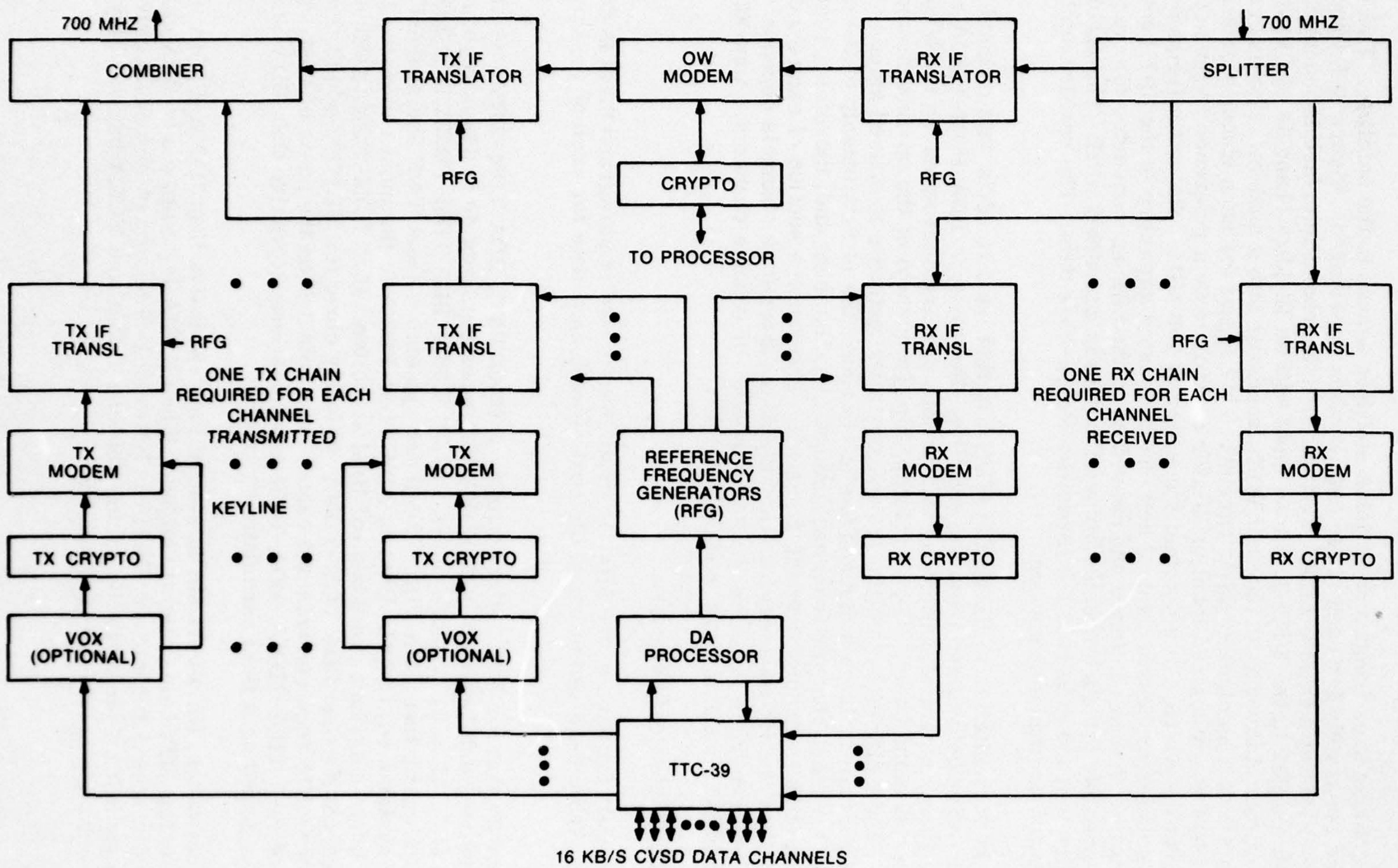


Figure 6-7. DMA-FDMA.

Table 6-18. Cost, C.

CANDIDATE DESCRIPTION			COST*		
DEMAND-ASSIGNMENT SYSTEM TYPE	MULTIPLEX TECHNIQUE	MULTIPLE ACCESS TECHNIQUE	FLTOPS	GMF	DCS
BDA-reservation	TDM	TDMA	1.324	4.416	1.665
	TDM	FDMA	4.587	40.899	16.003
	FDM	FDMA	2.055	23.694	11.869
BDA-TASI	TDM	TDMA	1.445	5.8125	2.1215
	TDM	FDMA	4.231	36.803	14.098
	FDM	FDMA	1.999	16.1715	7.4595
DAMA-reservation	NA	TDMA	1.325	4.422	1.6755
	NA	FDMA	2.244	25.698	12.597
DAMA-reservation with VOX	NA	FDMA	2.589	27.444	13.356
*Estimated production cost in millions of dollars.					

6.2.4 SHF Recommendations

The results of applying all the evaluation criteria (S, F, and C) are summarized in table 6-19 based upon the data listed in tables 6-8, 6-16, and 6-18. It should be noted that all final candidates treat data as switched traffic and do not use priority protocol.

6.2.4.1 FLTOPS

Table 6-19 reveals that for FLTOPS, DAMA is far superior to BDA when considering the required number of satellite channels. This is caused by the fact that FLTOPS is composed of many small users, each of which has little originating traffic. Due to the small amount of traffic both DAMA-TDMA and DAMA-FDMA require the same availability for frequency assignments. Therefore, system cost is the only difference between DAMA-TDMA and DAMA-FDMA with DAMA-TDMA appearing to be slightly less expensive. However, the design of the DAMA-TDMA system does not include equipment redundancy that would be required in any practical system design to eliminate single point failure. The inclusion of redundancy into DAMA-TDMA would raise the system cost to equal the cost of DAMA-FDMA and would necessitate selecting the optimum candidate by some other evaluation criteria.

Table 6-19. Summary of Evaluation Criteria Application Results.

CANDIDATE DESCRIPTION			EVALUATION CRITERIA APPLICATION RESULTS											
DA SYSTEM TYPE	MULTIPEX TECHNIQUE	MULTIPLE ACCESS TECHNIQUE	FLTOPS				GMF				DCS			
			S	F		*C	S	F		*C	S	F		*C
				RX & TX	TX ONLY			RX & TX	TX ONLY			RX & TX	TX ONLY	
BDA-	TDM	TDMA	133	0.890	0.780	1.3	2304	0.996	0.992	4.4	1176	0.976	0.952	1.7
Reservation	TDM	FDMA	133	0.820	0.010	4.6	2304	0.974	0.250	40.9	1176	0.903	0.120	16.0
	FDM	FDMA	133	0.820	0.010	2.1	2304	0.974	0.250	23.7	1176	0.903	0.120	11.9
BDA-	TDM	TDMA	122	0.890	0.780	1.4	1302	0.991	0.984	5.8	622	0.952	0.897	2.1
TASI	TDM	FDMA	122	0.810	0.010	4.2	1302	0.965	0.110	36.8	622	0.875	0.050	14.1
	FDM	FDMA	122	0.810	0.010	2.0	1302	0.965	0.110	16.2	622	0.875	0.050	7.5
DAMA-	N/A	TDMA	41	0.890	0.780	1.3	1388	0.994	0.988	4.4	784	0.967	0.939	1.7
Reservation	N/A	FDMA	41	0.890	0.780	2.2	1388	0.985	0.970	25.7	784	0.945	0.897	12.6
DAMA Reservation With VOX	N/A	FDMA	41	0.890	0.780	2.6	1388	0.985	0.970	27.4	784	0.945	0.897	13.4

*Estimated production cost in millions of dollars.

6.2.4.2 GMF

Table 6-19 indicates that BDA-TASI requires the fewest satellite channels (1302) to satisfy the GMF requirement which is 86 channels less than DAMA-reservation and 1002 channels less than BDA-reservation. The difference between BDA-TASI and DAMA-reservation is small so that the selection process must use a different criterion.

The mobile GMF terminal must operate in many different locations, and hence, should use a DA candidate that encounters the fewest problems getting frequency assignments. Thus, for the GMF, the selected DA candidate should possess the highest probability of obtaining frequency assignments. Both BDA-TASI and BDA-reservation using FDMA meet this requirement, but BDA-reservation was eliminated earlier because it required more satellite channels. Therefore, using F as the evaluation criterion, BDA-TASI using FDM-FDMA is the superior candidate.

However, BDA-TASI using FDM-FDMA is not the least expensive candidate. Rather, DAMA-TDMA costing $4.4M and BDA-TASI using TDM-TDMA costing $5.8M are much less expensive while requiring approximately the same number of satellite channels. Therefore, the choice between BDA-TASI using FDM-FDMA and either DAMA-TDMA or BDA-TASI using TDM-TDMA can only be made after the most important evaluation criterion has been identified. If cost is the determining factor, then both DAMA-TDMA and BDA-TASI using TDM-TDMA are equally good. However, if the probability of receiving frequency assignments is the most critical, then BDA-TASI using FDM-FDMA is best.

6.2.4.3 DCS

The DCS network is made up of a relatively few, large, stationary terminals, each having a large amount of traffic. BDA-TASI using FDMA is superior to all other candidates in requiring the fewest number of satellite channels and having the highest probability of receiving frequency assignments. However, as with the GMF, BDA-TASI using TDM-TDMA is considerably less expensive. DAMA-TDMA is also less expensive than BDA-TASI using FDM-FDMA but requires 25 percent more satellite channels.

Therefore, no one candidate is best for the DCS using all three evaluation criteria. Clearly, BDA-TASI requires the fewest satellite channels. The optimum choice of baseband multiplex technique and satellite multiple access technique depends on the criteria used. For lowest cost, BDA-TASI using TDM-TDMA is the superior choice. However, for the least amount of frequency assignment problems, BDA-TASI using FDM-FDMA is better.

6.3 HARDWARE DESCRIPTION OF FINAL SHF CANDIDATES

Two of the final demand-assignment candidates for SHF are DAMA-reservation and BDA-TASI. In this section we will review the options selected and describe possible hardware and operational protocol that could be used to implement the selected systems. All systems use 16 kb/s continuously variable slope delta (CVSD) modulation for voice and a 2400-b/s bit rate for data. It is assumed that all landline inputs are demodulated, decrypted, and concentrated at the satellite terminal by the central switch and that the basic BDA discipline is handled by a standard central office switch such as the AN/TTC-39. If the input lines are analog voice, it is further assumed that the central switch provides the CVSD modems. Because of the relatively small amount of data traffic, there is little to be gained in handling data separately from voice. The central switch will also provide the priority control for both voice and data. Again, although priority protocol for data does not improve system operation measurably on the SHF links, it is a standard part of the message handling

capability of some central switches and will therefore be assumed. Message destination is determined and properly routed into the satellite terminal via the central switch.

6.3.1 DAMA-Reservation

A simplified block diagram of the DAMA-reservation satellite terminal is shown in figure 6-7. The I/O lines may be analog voice, digital voice, or message data traffic. All digital signals may be encrypted or clear test. Signaling and supervision of these lines would be in accordance with current military and/or commercial standards, and priority control can be incorporated if desired. The central switch will interface between the satellite trunking circuits and the landline loops or trunks and will handle all crypto, priority, and control on the landline side of the circuit and will store and forward message traffic. Satellite traffic will be routed from the switch to the satellite TDM multiplexer and from the satellite TDM demultiplexer to the switch. The control functions between the switch and the satellite TDM system will be routed via common channel signaling through the terminal control processor. No encryption is used on any of the information control lines between the central switch and the TDMA system.

The DA processor monitors all control and supervisory messages from the central switch and from the central controller of the satellite network and issues control and supervisory messages to the central switch and to the central controller of the satellite network.

The baseband buffer unit stores information and control packets coming from the central switch and DA processor, respectively. This digital data is encrypted, packet by packet, by a time-of-day crypto system using a crypto key locked to the packet and frame number of the TDMA system. These packets are read out by the modem in the proper time slot by the transmit modem. The modem times the packets into the proper time slots and modulates the carrier to the SHF transmitter upconverter.

The satellite channel is received by the SHF satellite receiver and down-converted to the if frequency of the modem demodulator. The received TDMA packets are sent to the TDMA demultiplexer where the packets are separated and decrypted. The output information packets are stored and read out at the appropriate rate to the central switch. Control or orderwire packets are transmitted as packets to the DA processor.

If a call is initiated on the landline circuits, a request for a voice or data channel is issued over the control line between the switch and the processor, giving the destination, priority, and other pertinent data. The DA processor then initiates a control packet to the central control station requesting a TDMA time slot. This control packet is transmitted to and stored in the TDMA multiplexer for transmission on the assigned TDMA orderwire slot or on an ALOHA orderwire slot. The orderwire slots are monitored by the central control station. The central control station either honors the request for a channel by transmitting a control packet on the central control station's time slot indicating which time slot is to be used for both the calling and called parties, or denies the request by sending a denial of request control packet. The satellite-terminal DA processor monitors all control messages from the satellite control station. If the request for channel was denied, this information is sent via the control line to the central switch which sends a busy signal to the calling party. If the request was honored, then the processor tells the switch to assign an output and input circuit for this call. The switch tells the processor which circuits were assigned, and the processor tells the TDM multiplexer and demultiplexer which time slots these lines are to be assigned to.

At the terminal being called, the central control messages are also monitored and it assigns lines and time slots to set up the call. If the call is completed, these lines and slots are

held for the duration of the call. If the called party is busy, the switch informs the processor and the processor originates a busy message to the central control station. The central control station then transmits the appropriate control message, and the time slots are put back into the pool of available channels. The same sequence of actions occurs if either the called or calling party hangs up. In addition, the central control station monitors all traffic and, if no transmissions are monitored for a specified period of time on a given time slot, the appropriate busy messages are sent to the terminals and the time slots are placed back into the pool of available channels.

The receiving modem monitors orderwire transmissions originated by the terminal to perform round-trip timing so that the transmitted packets arrive at the satellite in the proper time slot. Some 40 bits of guard time are provided between packets to allow for timing errors. Each packet consists of a preamble of some 80 bits, used for carrier lock, bit sync, and terminal identification, and an information block consisting of approximately 1,500 bits. In order to gain net entry, the control terminal will attempt to provide periodically a number of idle continuous time slots. When this happens, the control terminal will authorize short timing transmissions in these time slots in order to provide round-trip timing for new stations entering the network.

6.3.2 BDA-Reservation With TASI

A simplified block diagram of a BDA-reservation system with TASI using an FDM-FDMA multiplex/multiple-access system is shown in figure 6-6. As in the case of the DAMA-reservation system, the central switch takes care of the switching, digitizing, COMSEC, priority, and control of the input voice and data landline traffic and sends and receives appropriate control messages to the DA processor. In this BDA application, however, the central switch functions more nearly as a normal exchange type switching concentrator. When a customer requests service by going off-hook, the central switch is enabled to accept a request for service from the line in the form of the number of the called party. The central switch examines the input lines to the TASI processor for an unused line. If an idle line is found, the central switch signals the DA processor to try to establish a voice circuit to the called party. The DA processor places a request for connection in its orderwire time slot in the FDM OW channel. This request is transmitted when the orderwire terminal time slot come up. The terminal to which the call is placed monitors the orderwire time slot and receives the request for a connection. The called DA processor examines the availability of lines to the TASI processors and, if capacity is available, signals the central switch to ring the called party. As soon as the called party goes off-hook, a channel is assigned to the called party into the TASI transmit processor and out of the TASI receive processor by the central switch, and the DA processor is informed that the call is complete. The DA processor sends a control packet to the OW channel modem for transmission to the calling terminal informing it that the connection has been made. The calling DA processor then signals the central switch and the central switch assigns a TASI input and output line to the calling party. The TASI transmit processor monitors voice activity and assigns a transmit output line, if available, to the busy channel. The TASI transmit processor simultaneously sends a control message through the DA processor to inform the other terminal of the FDM channel assignment being made. The other terminal then connects this FDM channel to the desired party through the TASI receive processor. The inputs to the assigned FDM channel modems are assembled into a sequence of digital packets, encrypted using time-of-day type synchronization. These packets are transmitted continuously under control of the DA processor.

6.4 REFERENCES

1. CCITT Blue Book, Vol II, Geneva, 1965, p 299.
2. Siemens, Telephone Traffic Theory Tables and Charts, Part I, 1974, Munich, Germany.

The UHF user models in section 4 will now be used to evaluate the candidate UHF assignment systems by using the evaluation criteria developed in section 2. Since the number of systems to be evaluated is large, we will use simplified user models and a simplified evaluation criterion in making an initial candidate selection in order to eliminate the poorest of the candidates from detailed analysis.

7.1 INITIAL UHF CANDIDATE SELECTION

For the simplified user models, we will assume the total busy-hour traffic intensity is distributed equally among the terminals and that the maximum allowable mean system waiting time is specified, rather than the maximum desired waiting time, as a function of message priority. The initial selection will be made on the basis of minimizing the number of 25-kHz channels required to provide the users with the required grade of service.

We will consider the candidate assignment systems listed in table 7-1. For the UHF models, only data traffic is considered, and we assume only store-and-forward type operations. In store-and-forward operations, the BDA technique is the discipline used in handling the store-and-forward queue. BDA, therefore, is an intrinsic part of store-and-forward systems and will not be addressed as a separate issue. Pure ALOHA is not considered because slotted ALOHA will give better performance in all cases (appendix B).

For store-and-forward traffic, we are primarily interested in minimizing the number of satellite channels required to accommodate a given user model traffic during the busy hour while providing an acceptable system waiting time. The system waiting time is the time elapsed from the submission of the entire message at the transmitting terminal to the successful reception of the entire message at the receiving terminal. The mean system waiting time, W, has been analyzed for each of the candidate assignment systems in section 5 and in appendix B. The number of users or terminals that a satellite channel will support using a particular assignment technique is found by applying the equations to the user models. The allowed mean system waiting time, W, will be taken as 120 seconds.

In all user models, the message length, ℓ, is exponentially distributed and the message interarrival times are random with an exponential distribution. The parameters of all candidate assignment systems have been chosen in order to maximize the traffic capacity for a given mean system waiting time. Therefore, the results are the best that can be achieved within the constraints of the generic assignment system type. The assumed parameters are shown in table 7-1.

Table 7-1. Assignment System Parameters.

SYSTEM TYPE	ASSUMED SYSTEM PARAMETERS
Reservation assignment plus random-assignment slotted ALOHA orderwire	Message preamble: a_1 = 120 bits. Reservation message: a_2 = 120 bits.
Reservation assignment plus fixed-assignment TDMA orderwire	Message preamble: a_1 = 120 bits. Reservation message: a_2 = 120 bits.
Polled assignment	Gaps between user transmission: 1/4 second.
Random-assignment slotted ALOHA	Packet preamble: a_1 = 120 bits. Information bits per packet: optimum $b = \sqrt{2 a_1 \overline{\ell}}$ * Random retransmission spread: 15 slots (K = 15).
Fixed-assignment FDMA (ideal)	Capacity loss due to multiple access: none.
Fixed-assignment TDMA	Packet preamble: a_1 = 120 bits. Information bits per packet: optimum $b = \sqrt{2 a_1 \overline{\ell}}$ *
* $\overline{\ell}$ = mean number of bits in a message.	

7.1.1 Initial Evaluation of FLTOPS

The FLTOPS traffic is described in section 4. The user parameters are summarized in table 7-2. The traffic generated by large, medium, and small ships is vastly different, so that one can consider various means of dividing the channel capacity among the users. For example, two satellite channels could be assigned to large ships, and the medium and small ships could share another satellite channel.

The last two columns show combinations of small-, medium-, and large-ship traffic in terms of an equivalent number of small ships so that the total traffic of all of the equivalent small ships is equal to the total traffic in the network. This gives a terminal count appreciably larger than the actual number of terminals in the system.

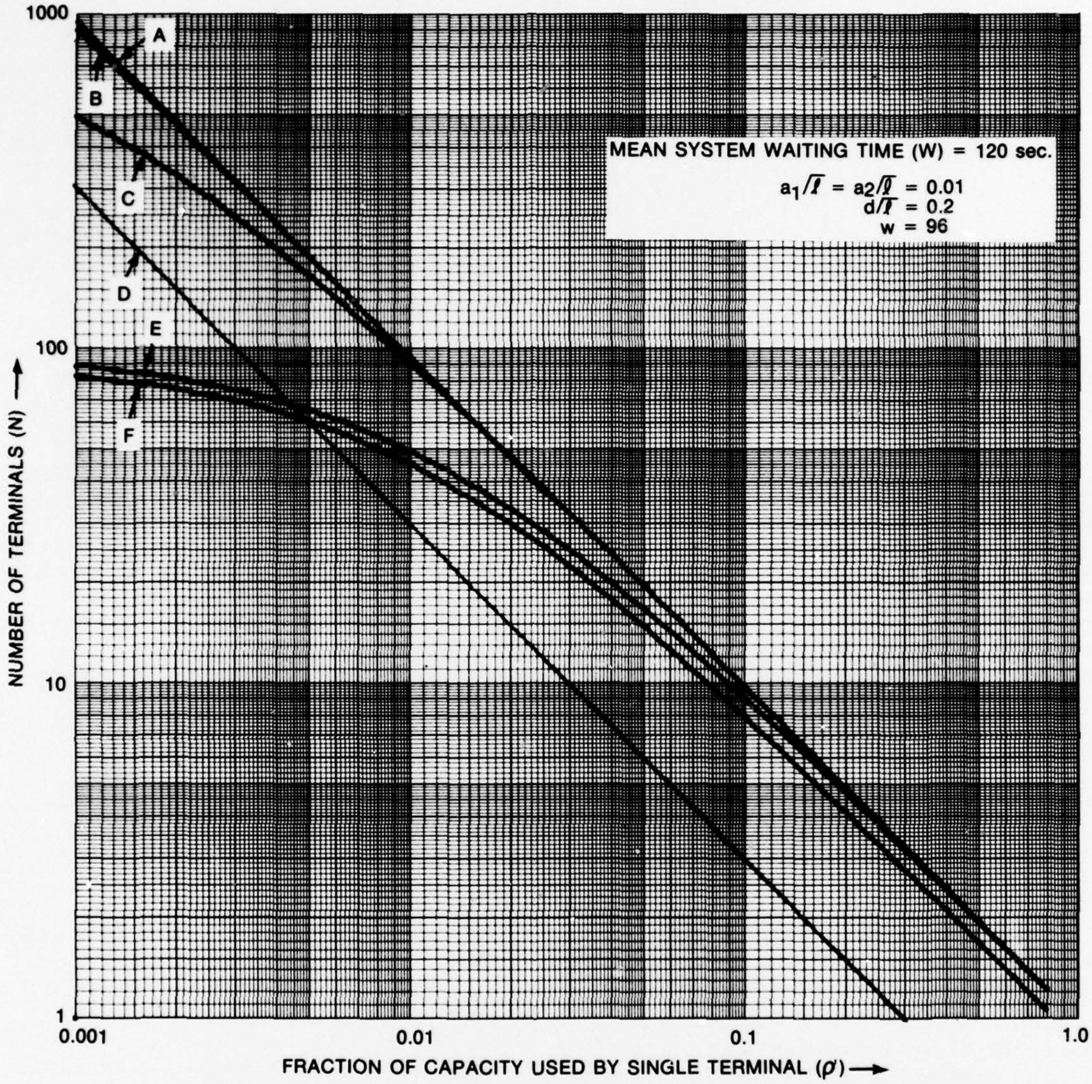
Table 7-2. FLTOPS System Parameters.

ITEM	SYMBOL	UNITS	LARGE SHIPS	MEDIUM SHIPS	SMALL SHIPS	COMBINED MEDIUM PLUS SMALL SHIPS (SMALL-SHIP EQUIVALENT)	COMBINED TOTAL - SMALL, MEDIUM, AND LARGE (SMALL-SHIP EQUIVALENT)
Number of terminals	N	#	10	50	100	600	1,600
Channel bit rate	r	b/s	9.6K	9.6K	9.6K	9.6K	9.6K
Mean message length	$\bar{\ell}$	b	12K	12K	12K	12K	12K
Message generation rate per terminal	λ'	m/s	8.7×10^{-2}	8.7×10^{-3}	8.7×10^{-4}	8.7×10^{-4}	8.7×10^{-4}
Terminal utilization	ρ'		1.09×10^{-1}	1.09×10^{-2}	1.09×10^{-3}	1.09×10^{-3}	1.09×10^{-3}
Total utilization	ρ		1.09	0.545	0.109	0.654	1.74
Mean waiting time	W_{max}	s	120	120	120	120	120
Normalized waiting time	w_{max}		96	96	96	96	96

The supportable bit rate, using the 25-kHz FLTSAT channels, is 9,600 b/s (see section 4) and the normalized waiting time, $w = W/(\ell/r)$, is 96. The number of terminals a satellite channel can handle as a function of the terminal utilization factor, ρ', for w equal to 96 is shown in Figure 7-1. The numbers of terminals a channel can handle for large, medium, and small ships are shown in tables 7-3, 7-4, and 7-5 respectively. It will be noted that a single channel can handle nine large ships using either polled assignment or reservation assignment. TDMA can handle seven large ships. Thus, TDMA, polled assignment, reservation assignment with TDMA orderwire, and reservation assignment with slotted ALOHA orderwire are all tentative candidates if the large ships are to be handled on a separate channel. Two satellite channels would be required to handle all large-ship traffic regardless of which of these access systems is chosen.

Table 7-3. Satellite Channel Utilization for FLTOPS Large Ships Only (From Figure 7-1 With $\rho' = 0.109$).

TYPE OF ACCESS	CHANNEL UTILIZATION FACTOR, ρ	NUMBER OF TERMINALS (N) PER CHANNEL
FDMA	0.87	8
TDMA	0.76	7
Polled	0.98	9
Slotted ALOHA	0.33	3
Reservation with TDMA orderwire	0.98	9
Reservation with slotted ALOHA orderwire	0.98	9



LEGEND		
CURVE	TYPE SYSTEM	EQU. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED ASSIGNMENT	B-37
D	RANDOM ASSIGNMENT-SLOTTED ALOHA	B-41
E	FIXED ASSIGNMENT-FDMA (IDEAL)	B-32
F	FIXED ASSIGNMENT-TDMA	B-34

Figure 7-1. Comparison of Access Systems for the FLTOPS.

The channel utilization for medium ships using various access means is shown in table 7-4. Here polled assignment, reservation assignment with TDMA orderwire, and reservation assignment with slotted ALOHA orderwire can handle about 80 terminals. These are markedly superior to all other techniques and are therefore the primary candidates if the medium ships are handled by a separate channel. Since there are only 50 medium ships in the FLTOPS, a single satellite channel will provide more capacity than required.

The channel utilization for small ships is shown in table 7-5. In this case, polled assignment can handle 440 ships; reservation assignment with TDMA orderwire can handle 780 ships; and reservation assignment with slotted ALOHA orderwire can handle 800 ships. Since there are only 100 small ships, one satellite channel will provide many times the capacity required.

Since a single satellite channel provides more than enough capacity for either the medium- or small-ships network alone, it is instructive to combine these two networks into a single network. A lower bound on the obtainable channel utilization is obtained by replacing a single medium ship with ten small ships, since the traffic generation rate for the medium ship is ten times that of the small ship. From table 7-2 it will be noted that the small-ship equivalent of this combined network would have 600 ships. From table 7-5, it will be seen that if reservation assignment with either a TDMA or a slotted ALOHA orderwire is used, a channel can provide service for all small and medium ships. If separate large-ship channels are employed, the total requirement for the FLTOPS system is three satellite channels.

Table 7-4. Satellite Channel Utilization for FLTOPS Medium Ships Only (From Figure 7-1 With $\rho' = 0.0109$).

TYPE OF ACCESS	CHANNEL UTILIZATION FACTOR, ρ	NUMBER OF TERMINALS (N) PER CHANNEL
FDMA	0.52	48
TDMA	0.46	42
Polled	0.89	82
Slotted ALOHA	0.30	28
Reservation with TDMA orderwire	0.94	86
Reservation with slotted ALOHA orderwire	0.94	86

Table 7-5. Satellite Channel Utilization for FLTOPS Small Ships Only (From Figure 7-1 With $\rho' = 0.00109$).

TYPE OF ACCESS	CHANNEL UTILIZATION FACTOR, ρ	NUMBER OF TERMINALS (N) PER CHANNEL
FDMA	0.09	86
TDMA	0.08	76
Polled	0.48	440
Slotted ALOHA	0.31	280
Reservation with TDMA orderwire	0.85	780
Reservation with slotted ALOHA orderwire	0.85	800

Another alternative is to combine all ship sizes into a single network. Again, a lower bound on the utilization can be obtained by replacing each large ship with 100 small ships and each medium ship with 10 small ships, so that the equivalent small-ship network contains 1,600 small ships. From table 7-5, it is seen that all capacity requirements can be met using three satellite channels employing reservation assignment with either TDMA or slotted ALOHA orderwire. The resultant candidate systems are shown in table 7-6.

Table 7-6. FLTOPS System Candidates.

SYSTEM TYPE	REQUIRED NUMBER OF 25-kHz SATELLITE CHANNELS*
Divided network	
Large-ship network (TDMA, polled assignment, or reservation assignment with either TDMA or slotted ALOHA orderwire)	2
Medium- and small-ship network (reservation assignment with either TDMA or slotted ALOHA orderwire)	1
Total requirements	3
Combined network	
Large-, medium- and small-ship network (reservation assignment with either TDMA or slotted ALOHA orderwire)	3
Total requirements	3
*25-kHz FLTSAT channels.	

Enough system detail has been included in the analysis of the various access systems to permit a realistic comparison. However, unnecessary detail has been excluded from the descriptions of the systems to limit the degree of definition detail and thus limit, to a reasonable quantity, the potential number of systems which must be considered. To this end we have optimized each design as necessary. In some cases, these optimized designs have been perhaps overly idealistic. This is particularly true in some applications for fixed-assignment FDMA and for random-assignment slotted ALOHA. In spite of these idealistic assumptions, these two systems have not been proven the best for the FLTOPS applications.

7.1.2 Initial Evaluation of GMF Systems

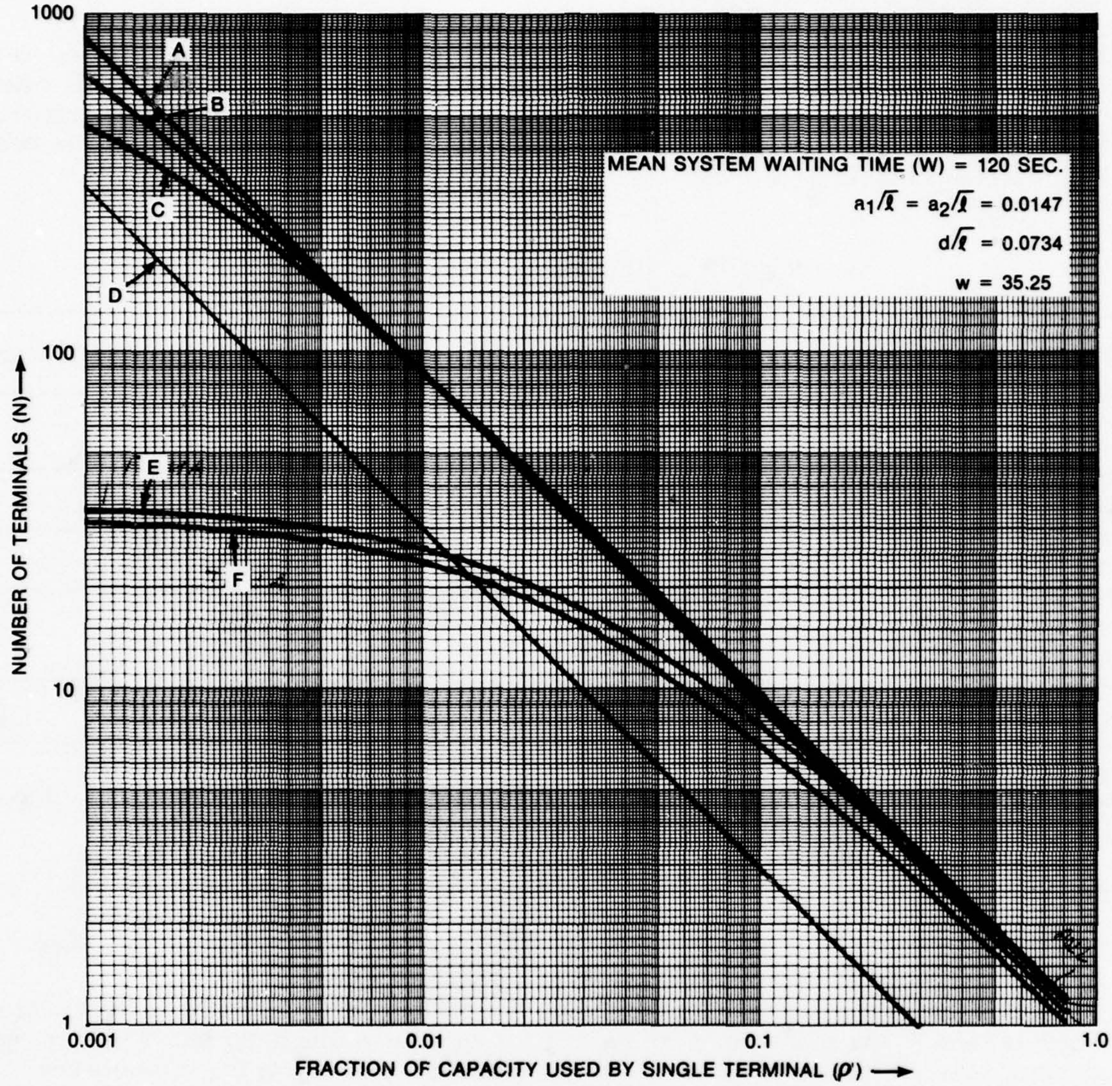
We will now perform a simplified analysis for various assignment techniques applied to GMF traffic. It is shown in section 4 that the FLTSAT 25-kHz channels will support a bit rate of 4,800. Current Army architecture, however, calls for operation at 2,400 b/s per channel, and this bit rate will therefore be used in the analysis. The parameters presented in section 4 are summarized in table 7-7.

Table 7-7. GMF System Parameters.

ITEM	SYMBOL	UNITS	TOTAL TERMINALS
Number of terminals	N	#	210
Channel bit rate	r	b/s	2.4K
Mean message length	$\bar{\ell}$	b	8,170
Message generation rate per terminal (busy hour)	λ'	m/s	17.6×10^{-3}
Terminal utilization	ρ'		59.9×10^{-3}
Total utilization	ρ		12.6
Mean wait time	W_{max}	s	120
Normalized wait time	w_{max}		35.25

Table 7-7 gives the number of terminals, N; the channel operating bit rate, r; the mean message length in bits, $\bar{\ell}$; the mean message generation rate for a single terminal in messages per second, λ'; the utilization factor for a single terminal, $\rho' = \lambda'\bar{\ell}/r$; the total channel utilization factor for all terminals if all terminals could be accommodated on a single channel, $\rho = N\rho'$; the maximum allowable mean system waiting time in seconds, W_{max}; and the normalized maximum system waiting time measured in mean message durations, $w = W_{max}/(\bar{\ell}/r)$.

The number of terminals, N, that can be supported on a satellite channel as a function of the single-terminal utilization factor, ρ', is plotted in figure 7-2. At a single-terminal channel utilization factor of 0.06, it will be noted that polled assignment or either of the two reservation-assignment systems can support approximately 16 terminals, thus obtaining an overall channel utilization factor of about 96 percent. Note also that these three assignment systems continue to perform well for a range of the single-terminal utilization factor, ρ', of from 0.001 to 1.0. Thus, the choice of the best access system is not sensitive to ρ'. Also, for ρ' equal to 0.06, note that ideal FDMA, TDMA, and slotted ALOHA systems will support less than 11 terminals, for an overall utilization of less than 60 percent. These results are tabulated in table 7-8.



LEGEND		
CURVE	TYPE SYSTEM	EQ. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED ASSIGNMENT	B-37
D	RANDOM ASSIGNMENT-SLOTTED ALOHA	B-41
E	FIXED ASSIGNMENT-FDMA (IDEAL)	B-32
F	FIXED ASSIGNMENT-TDMA	B-34

Figure 7-2. Comparison of Access Systems for the GMF System.

Table 7-8. Channel Utilization for the GMF System for Various Access Systems (From Figure 7-2 With $\rho' = 0.06$).

TYPE OF ACCESS	CHANNEL UTILIZATION FACTOR, $\rho = N\rho'$	NUMBER OF TERMINALS PER 25-kHz CHANNEL
FDMA	0.66	11
TDMA	0.60	10
Polled	0.96	16
Slotted ALOHA	0.30	5
Reservation with TDMA orderwire	0.96	16
Reservation with slotted ALOHA orderwire	0.96	16

The theoretical curve of figure 7-2 shows that the ideal FDMA system can support 11 terminals, giving a utilization factor, ρ, of 66 percent. Less than one-third of this capacity could be supported in the actual system because of power balance problems and bandwidth constraints for the case of a hard limiting 25-kHz channel. However, since FDMA does not turn out to be a primary candidate, even if this total capacity could be achieved, the actual achievable capacity will not be pursued further. Figure 7-2 shows that TDMA will support 10 terminals and yield a utilization factor, ρ, of 60 percent. This is a realistic result based on a preamble length plus guard time of 120 bits and an optimum slot length of 1,400 bits.

For polled-assignment systems with a preamble of 120 bits and a propagation delay of 600 bits (0.25 s), the figure shows that the channel will support 16 terminals, yielding a utilization factor of 96 percent.

Slotted ALOHA will support (at most) 5 terminals, which gives a utilization factor, ρ, of 30 percent. Actually, slotted ALOHA systems will be unstable for a ρ much greater than 25 percent, so that perhaps only 4 terminals could be served practically.

For reservation assignment with a TDMA orderwire and with a message preamble and orderwire message length of 120 bits each, it will be noted that 16 terminals can be supported. This gives a utilization factor of 96 percent. At this value of ρ, approximately 1.6 percent of the time should be devoted to the orderwire function and 98.5 percent to message transmission.

In the analysis (appendix B) of reservation assignment with a slotted ALOHA orderwire, we assumed there would be no appreciable increase in waiting time due to propagation delay. This can be achieved by using the channel for transmission of messages while waiting for the orderwire message blocks to propagate to the satellite and back. Figure 7-2 shows that the

channel will support 16 terminals, assuming a message preamble and an orderwire message length of 120 bits each. The utilization factor, ρ, is 96 percent.

Table 7-8 is provided for assistance in comparing the performance of the systems. It will be noted that reservation assignment with a slotted ALOHA orderwire, reservation assignment with a TDMA orderwire, and polled-assignment systems all give the same performance. The next best systems, FDMA and TDMA, provide about two-thirds the capacity of the three best systems listed above.

Polled assignment and reservation assignment with either a TDMA or slotted ALOHA orderwire are all competitive, and all three must be retained for more detailed analysis. It will be noted that each of the candidate systems will handle 16 terminals. It would, therefore, be necessary to use 14 satellite channels in order to satisfy the total requirement of 210 terminals of the GMF system. It should be noted further that these results are not very sensitive to the single-terminal utilization factor.

7.1.3 Initial Selection of Candidate UHF DA Systems

From the analysis of the FLTOPS and the GMF systems, it was generally found that neither fixed-assignment nor random-assignment systems provide sufficient utilization of the satellite channels to be considered as candidates. It was also found that reservation assignment provides high channel utilization in all cases and provides the greatest flexibility of all systems investigated. Reservation assignment is therefore the primary candidate for applications. The utilization efficiency was also high for polled assignment in all applications. It is therefore necessary to carry this as an initial candidate system. Time division multiple access (TDMA) proved to be fairly efficient for the large-ship network, and it will be maintained as a candidate for this application only.

Reservation assignment with a slotted ALOHA orderwire is by far the most flexible in handling a mix of high- and low-traffic terminals and in allowing for wide changes in the number and type of terminals in the network. Its only shortcoming is the possibility of overload of the orderwire channel.

Reservation assignment with a time division multiple access orderwire avoids the problem of orderwire overload while still maintaining the intrinsic capability to provide precedence protocol. However, the system must be augmented to allow new stations to enter the network.

Polled assignment provides high channel-utilization efficiency for a few high-duty-cycle users.

7.2 FINAL UHF CANDIDATE SELECTION

In paragraph 7.1, an initial selection of UHF candidates was made on the basis of simplified modeling. It is now necessary to make a final selection of a candidate on the basis of more detailed user-traffic models and demand-assignment system models. This final analysis will include the consideration of traffic variation between the terminals of a network, diurnal traffic variation, priority protocol, and network control traffic. The terminal-to-terminal traffic variations for GMF are given in section 4. For FLTOPS, the terminal-to-terminal distribution of traffic intensity will be assumed to be uniform over a range of zero to twice the mean busy-hour traffic intensity. Analyses of diurnal traffic variation and priority protocol are presented in section 5.

Using these data and analysis procedures, a detailed analysis of the number of satellite channels will be made for each of the initial candidate demand-assignment systems and for each UHF user model. The total system cost of each surviving candidate systems will be developed.

The demand-assignment candidates for detailed analysis are shown in table 7-9. Priority protocol is not used with polled assignment since polled assignment does not provide this capability except within the queue of a terminal. For fixed assignment, priority protocol is included, but this applies only to traffic within a single terminal.

Table 7-9. UHF Assignment Candidates for Detailed Analysis.

ASSIGNMENT SYSTEM TYPE	ORDERWIRE TYPE	PRIORITY PROTOCOL
*Fixed-assignment TDMA	None	No
		Yes
Polled assignment	None	No
Reservation assignment	TDMA	No
		Yes
	Slotted ALOHA	No
		Yes
*Fixed-assignment TDMA is a candidate for FLTOPS large ships only.		

7.2.1 Required Satellite Channel Capacity

The number of satellite channels required to support each of the UHF user models using each of the demand-assignment candidates of table 7-9 will now be calculated. For UHF, the satellites already use frequency division multiple access with 25-kHz channel spacing, so that FDMA is an intrinsic part of the UHF satellite design. The satellite channels are hard-limited, which precludes the efficient use of FDMA within a 25-kHz satellite channel. Thus, only TDMA is considered within a 25-kHz channel, and all UHF systems will therefore use FDMA or FDMA-TDMA multiple access.

The priority requirements for FLTOPS and GMF are shown in table 7-10. Each system will be sized so that the desired system waiting time for each priority class is not exceeded more than 1 percent of the time. If no priority protocol is used, all traffic must be handled as if it were the highest priority traffic, and the system waiting time for all message traffic must not exceed that desired for the highest priority more than 1 percent of the time.

7.2.1.1 Method of Sizing UHF Systems

Analyses are available for the mean system waiting time for all the assignment systems to be analyzed here. However, in the present analysis, we are required to determine the probability of exceeding the maximum desired system waiting time for each priority class.

Table 7-10. UHF User Priority Requirements.

PRIORITY DATA TRAFFIC	FLTOPS		GMF	
	PERCENT	MAXIMUM WAITING TIME (s)	PERCENT	MAXIMUM WAITING TIME (s)
Emergency	0.02	30	0.0	30
Flash	0.08	60	2.86	60
Immediate	5.0	300	28.64	300
Priority	42.0	3,600	68.5	3,600
Routine	52.9	10,800	0.0	10,800

7.2.1.1.1 Fixed-Assignment TDMA

In fixed assignment there is no demand assignment sharing of the channels, so one must deal with the traffic intensity of each terminal and allocate sufficient communications capacity for each user to meet the priority system waiting time requirements. The minimum message service rate, μ_i for each priority class is calculated for a terminal using the method of section 6, appendix B. The highest of these, μ_{max}, is determined and then used to size the terminal. Clearly, the minimum bit rate capacity required, r_{min}, is given by

$$r_{min} = \frac{\mu_{max} \bar{\ell}}{\epsilon}, \tag{7-1}$$

where $\bar{\ell}$ is the mean message length in bits and ϵ is the utilization efficiency. Utilization efficiency is defined as the mean message information bits divided by the mean total number of bits required to transmit the message. The efficiency is reduced by two factors: (1) the preamble bits, a_1, required per transmission packet, and (2) the number of bits wasted in the last packet due to the fact that the messages are not, in general, an even number of packets in length, thus leaving packets partically filled with blank characters. The optimum number of information bits in a packet, b_o, is given by

$$b_o = \sqrt{2 a_1 \bar{\ell}}, \tag{7-2}$$

where a_1 is the number of bits in the preamble. We shall use a value of a_1 of 120 bits and a value for b of 1500 bits which is close to optimum for both FLTOPS and GMF. The mean number of packets per message, $\overline{m}$, is

$$\overline{m} = \frac{1}{1 - \exp(-b/\bar{\ell})} \quad . \tag{7-3}$$

The mean number of total bits in a message, $\bar{\ell}'$, is therefore

$$\bar{\ell}' = \overline{m}\,(a_1 + b_o) = \frac{a_1 + b_o}{1 - \exp\,(-b/\bar{\ell})} \quad . \tag{7-4}$$

Finally, the utilization efficiency, ϵ, is given by

$$\epsilon = \frac{\bar{\ell}}{\bar{\ell}'} = \frac{\bar{\ell}\,[1 - \exp\,(-b/\bar{\ell})]}{a_1 + b} \, . \tag{7-5}$$

The total channel capacity can be divided into TDMA channels and the terminals assigned one or more of these channels, as required, to provide the required minimum bit rate.

7.2.1.1.2 Polled Assignment

For a polled-assignment system, the total busy-hour message generation rate, λ_T, is reduced by the time-spreading factor, K, of busy-hour traffic over the geographical area being served. For a uniform distribution of terminals over four time-zones, this factor is K = 2.5/3 = 0.8333. We have

$$\lambda_T' = K\,\lambda_T, \tag{7-6}$$

where λ_T' is the total busy-hour message generation rate, taking into account the time-zone spread of the terminals. (Refer to section 5.)

The average system waiting time, $\overline{W}$, for a queueing system without priority protocol is given by (equation B-148 of appendix B).

$$\overline{W} = \frac{-W_{m1}}{\ln(P_{m1})}, \tag{7-7}$$

where W_{m1} is the maximum desired system waiting time for the highest priority message, and P_{m1} is the allowed probability of exceeding this maximum desired system waiting time for priority-1 traffic. Equation B-37 of appendix B can be solved for $\rho = N\rho'$ to give

$$\rho = N\rho' = \frac{\overline{W}/(\bar{\ell}/r) - 1 - \frac{1}{2}\,(d/\bar{\ell})N}{\overline{W}/(\bar{\ell}/r) - \frac{1}{2}\,(d/\bar{\ell})}, \tag{7-8}$$

where N is the number of terminals in the network, $\bar{\ell}$ is the mean message length in bits, and d is the round-trip propagation delay in bits. But from the definition of ρ we have

$$\rho \;=\; \lambda(\bar{\ell}/r), \tag{7-9}$$

or

$$\lambda = \rho/(\bar{\ell}/r) , \tag{7-10}$$

but the actual message generation rate, $\lambda_T{}'$, must be less than or equal to that given by equation 7-1 (above), or

$$\lambda_T{}' \leq \rho/(\bar{\ell}/r). \tag{7-11}$$

If $\lambda_T{}'$ does not meet the requirements of equation 7-11, then $\lambda_T{}'$ must be reduced by dividing the terminals between several satellite channels until the $\lambda_T{}'$ for each channel meets the requirements of equation 7-11.

7.2.1.1.3 Reservation Assignment

In a reservation assignment system the total system waiting time consists of the sum of the time required to enter a request for service on the orderwire (queue entry time), the minimum time required for the central station to grant this request (turnaround time), the time the message spends in the virtual queue and the time required to transmit the message. The turnaround time, Δ, will be assumed to be a fixed duration that can be subtracted directly from the desired maximum waiting time for each priority class (t_i).

The cumulative probability distribution for the combined time for virtual queue waiting plus message service time, $P(w > t)$, is that for a simple M/M/1 queuing system and is given by

$$P(w > t) = 1 - e^{-t/\overline{w}} \tag{7-12}$$

where $\overline{w}$ is the sum of the mean queue waiting time and the mean message service time and is given by

$$\overline{w} = \frac{1}{\mu - \lambda} \tag{7-13}$$

where μ is the mean message service rate and λ is the mean message arrival rate. The mean message service rate, μ, is simply

$$\mu = \bar{\ell}'/r \tag{7-14}$$

where $\bar{\ell}'$ is the mean number of bits per message including all overhead bits and r is the channel bit rate.

The probability distribution of total waiting time is obtained by combining the probability distribution for queue entry time with that for message waiting time. The probability distribution for queue entry time depends on the type of orderwire used.

7.2.1.1.3.1 TDMA Orderwire

For a TDMA orderwire, the duration of a frame, F, is given by

$$F = \frac{1}{r}\left[Ca_2 + M(a_1 + b)\right] \tag{7-15}$$

where C is the number of orderwire slots per frame, M is the number of message blocks per frame and a_2 is the number of bits in a TDMA time slot. It will be assumed that there is a

TDMA orderwire time slot for each earth station so that C is also the number of stations or terminals in the network. When a message arrives at a terminal, the terminal must wait for the next orderwire time slot assigned to this terminal before it can transmit a request and thereby enter the message into the virtual queue at the central control station. This queue entry time is uniformly distributed over an interval of one frame so that the probability density function, $f_q(t)$, is

$$f_q(t) = \begin{cases} 1/F & o \leq t \leq F \\ o & \text{elsewhere} \end{cases} . \tag{7-16}$$

The probability density function for message waiting time is

$$f_m(t) = \frac{1}{\overline{w}} e^{-t/\overline{w}} \tag{7-17}$$

The total waiting time is the sum of the queue entry time plus the message waiting time and therefore the total waiting time probability density is

$$f_T(t) = \int f_q(t - x) f_m(x) \, dx \tag{7-18}$$

and the cumulative probability function is

$$P(w < t) = \int_o^{\min (F,t)} \int^{t-y} \frac{1}{F} \frac{1}{\overline{w}} e^{-x/w} \, dx \, dy$$

$$P(w < t) = \begin{cases} t/F - (1 - e^{-t/\overline{w}}) \, \overline{w}/F & t \leq F \\ 1 + e^{-t/\overline{w}}(1 - e^{T/\overline{w}}) \, \overline{w}/F & t > F \end{cases} \tag{7-19}$$

The mean message waiting time, $\overline{w}$, is given by equation 7-13 and the mean service rate, μ, is given by equation 7-14 where $\overline{\ell}'$ is given for a TDMA orderwire by

$$\overline{\ell}' = \overline{m} \left[a_1 + b + \frac{C}{M} a_2 \right] \tag{7-20}$$

where $\overline{m}$ is the mean number of message slots required to transmit a message and is given by equation 7-3.

If the maximum desired waiting time for priority class n traffic is t_n, then the probability of exceeding this for priority class n messages is given approximately by*

$$P(w > t_n) = \left\{ \begin{array}{ll} 1 - (1 - e^{-(t_\eta - \Delta)/\overline{w}_\eta}) \overline{w}_\eta/F - t_\eta/F & \text{for } t_\eta \leq F + \Delta \\ e^{-(t_\eta - \Delta)/\overline{w}_\eta} (e^{F/\overline{w}_\eta} - 1) \, \overline{w}_\eta/F & \text{for } t_\eta > F + \Delta \end{array} \right\} \tag{7-21}$$

---

*This approximation assumes that very few higher priority messages exceed the desired waiting time for a lower priority message.

where $\overline{w}_n$ is given by

$$\overline{w}_n = \frac{1}{r/\overline{\ell}' - \sum_{i=1}^{n} \lambda'_i} \tag{7-22}$$

and where λ'_i is the message generation rate for priority i messages.

7.2.1.1.3.2 Slotted ALOHA Orderwire

For a reservation assignment system with a slotted ALOHA orderwire, the time required to grant a request for a channel and the probability distribution of the time required to queue and service a message is the same as for reservation assignment system with a TDMA orderwire. However, the probability distribution of the queue entry time is different.

A frame consists of C orderwire slots of a_2 bits each and M message blocks of $a_1 + b$ bits each. A terminal requests a reservation for a specified number of message blocks and a given message priority by transmitting a request in an orderwire time slot. The terminal selects one of the C slots in the next frame at random to transmit this request. The terminal monitors the satellite rebroadcast of this request. If this monitoring determines that the request was interfered with, then a repeat of the request is initiated in one of the C orderwire slots at random in the next frame. This process is repeated until the request messages get through without interference. If C is 8 or greater and the required mean throughput is less than 25 percent of the orderwire slot capacity, then the circuit performs much as if each transmission were independent (see reference 3). The probability of an orderwire time slot being occupied by one and only one transmission, P_1, is given by

$$P_1 = Ge^{-G} \tag{7-23}$$

where G is equal to the average number of orderwire transmissions per time slot from all sources (see reference 3). Also the probability of a slot being unoccupied, P_o, is given by

$$P_o = e^{-G} \tag{7-24}$$

The probability of an orderwire request being transmitted without interference, P_{oK}, is therefore given by

$$P_{oK} = \frac{P_1}{1 - P_o} \tag{7-25}$$

The probability of requiring exactly i frames in order to successfully complete a request, P_i, is therefore

$$P_i = P_{oK} (1 - P_{oK})^{i-1} \tag{7-26}$$

The duration of a frame, F, is

$$F = C\, a_2 + M(a_1 + b) \tag{7-27}$$

To obtain the probability that the total time to get a message through will be greater than t_n we simply sum the probability of getting the request through in the first frame times the probability of exceeding $t_n - \Delta$ plus the probability of getting the request through in the second frame times the probability of exceeding a message waiting time of $t_n - \Delta - F$, etc, up to $t_n - \Delta - mF$ where m is the maximum integer such that $t_n - \Delta - mF > 0$ or

$$P(w > t_n) = \sum_{i=0}^{m} P_i \, e^{-(t_n - \Delta - iF)/\overline{w}_n} \tag{7-28}$$

Substituting from equation 7-26 gives

$$P(w > t_n) = \sum_{i=0}^{m} P_{oK} (1 - P_{oK})^{i-1} e^{-(t_n - \Delta - iF)/\overline{w}_n} \tag{7-29}$$

where $\overline{w}_n$ is given by equation 7-22, P_{oK} is given by equation 7-25 and F is given by equation 7-27.

In order to obtain $\overline{w}_n$ from equation 7-22, however, we must evaluate the mean number of total bits per message, $\overline{\ell}'$, including overhead bits. This is clearly given by

$$\overline{\ell}' = \overline{m}(a_1 + b + \frac{C}{M} a_2) \tag{7-30}$$

where $\overline{m}$ is given by equation 2-3. P_1 and P_0 are required in order to evaluate P_{oK}. Since we assume exactly one successful orderwire transmission per message, the message generation rate λ_T' must be equal to the number of successful orderwire transmissions per second or

$$\lambda_T' = \frac{P_1 K}{F} \tag{7-31}$$

so that

$$P_1 = \frac{\lambda_T' F}{K} \tag{7-32}$$

Now G can be obtained implicitly from equation 7-23 and this value of G can then be used to solve for P_0 in equation 7-24. Thus, it is now possible to evaluate equation 7-29 from given data.

7.2.1.2 Sizing of Final Candidate Systems

Each of the seven candidate assignment systems has been sized for each of the UHF user models in accordance with the procedures specified in the previous paragraphs. The overall results are presented in table 7-11. The calculations leading up to these results are shown in tables 7-12 through 7-18.

Table 7-11. UHF Network Satellite Channel Requirements.

SYSTEM TYPE	SATELLITE CHANNELS REQUIRED			
	FLTOPS			GMF
	LARGE SHIPS	MED AND SMALL SHIPS	LARGE, MED, AND SMALL SHIPS COMBINED	
Fixed-assignment TDMA				
Without priority	4			
With priority	3			
Polled assignment				
Without priority	2			18
Reservation assignment				
TDMA orderwire				
Without priority	2	2	4	21
With priority	2	1	2	14
Slotted ALOHA orderwire				
Without priority	2	1	3	20
With priority	2	1	2	14

Inspection of table 7-11 reveals that in all except three cases, the use of priority protocol reduced the number of satellite channels required to handle the traffic by one-third to one-half. The three cases in which there is no reduction in the number of satellite channels required are when reservation assignment is used. This is due to the fact that the potential savings are hidden by the quantization of the required satellite channels to an integral number. It is therefore concluded that the use of priority protocol will, in general, significantly increase the efficiency of utilization of the satellite channel.

For FLTOPS large ships, it will be noted that fixed assignment using TDMA requires 1.5 to 2.5 times the number of satellite channels required by the best of the reservation-assignment systems. Since the difference in hardware complexity is small, it is clear that a fixed-assignment cannot compete successfully with reservation assignment. This system, therefore, will not be costed. It will further be noted that the sum of the number of satellite channels required for large ships only and medium plus small ships only is always appreciably larger than the number of channels required for a single composite network of

Table 7-12. FLTOPS Large-Ship Fixed-Assignment TDMA Channel Requirements Calculation.

TERM NO	MSG GEN RATE, λi	WITHOUT PRIORITY				WITH PRIORITY			
		μ_{MAX} (msg/s)	r_{MIN} (b/s)	CHAN ASGN	TOTAL CHAN	μ_{MAX} (msg/s)	r_{MIN} (b/s)	CHAN ASGN	TOTAL CHAN
1	0.029	0.182	2,517	A	A + B + C + D = 4	0.1535	2,117	A	A + B + C = 3
2	0.029	0.182	2,517	B		0.1535	2,117	A	
3	0.058	0.211	2,916	A		0.1535	2,117	A	
4	0.058	0.211	2,916	B		0.1535	2,117	A	
5	0.087	0.241	3,316	C		0.1535	2,117	B	
6	0.087	0.241	3,316	C		0.1535	2,117	B	
7	0.116	0.270	3,716	D		0.1535	2,117	B	
8	0.116	0.270	3,716	D		0.1535	2,117	B	
9	0.145	0.298	4,116	A		0.1535	2,117	C	
10	0.145	0.298	4,116	B		0.1535	2,117	C	
TOTAL	0.870	2.405	33,167	-	4	1.5350	21,170	-	3

$r = 9{,}600$ b/s per channel

$a_1 = 120$ bits

$\bar{\ell} = 12{,}000$ bits

$b = 1500$

$$\epsilon = \frac{\bar{\ell}\left[1 - \exp\left(-b/\bar{\ell}\right)\right]}{a_1 + b} = 0.8704$$

large, medium, and small ships when priority protocol is used. We shall, therefore, retain for costing and final analysis of FLTOPS all reservation-assignment systems for combined large, medium, and small ships with priority protocol. The best of the assignment systems (reservation assignment with priority protocol) requires only two satellite channels.

For GMF it will be noted that in every case the inclusion of priority protocol reduces the number of satellite channels required. Since a polled-assignment system cannot provide

Table 7-13. FLTOPS Large-Ship Polled-Assignment Channel Requirements Calculation.

NO OF TERMINALS ON SINGLE CHANNEL, N	BUSY-HOUR MESSAGE GENERATION RATE, $\lambda_{T'}$	UTILIZATION, ρ	MAXIMUM ALLOWABLE MESSAGE GENERATION RATE, λ	COMMENT
10	0.7250	0.628	0.502	$\lambda < \lambda_T' \therefore$ N.G.
5	0.3625	0.726	0.581	$\lambda > \lambda_T' \therefore$ O.K.

Note: Can handle five terminals per channel; therefore, two channels are required.

$W_{m1} = 30$ s; $\bar{\ell} = 12{,}000$; $r = 9{,}600$; $1/2(d/\bar{\ell}) = 0.1$; $K = 0.8333$;

$P_{m1} = 0.01$; $d = 2{,}400$; $\bar{\ell}/r = 1.25$; $\lambda_T = 0.87$;

$\bar{W} = -W_{m1}/\ell n(P_{m1}) = 6.514$; $\bar{W}/(\bar{\ell}/r) = 5.21$; $\lambda_T' = K_{\lambda T} = 0.725$;

$$\rho = \frac{\bar{W}/(\bar{\ell}/r) - 1 - \frac{1}{2}(d/\bar{\ell})\ N}{\bar{W}/(\bar{\ell}/r) - \frac{1}{2}(d/\bar{\ell})}\ ; \quad \lambda = \rho/(\bar{\ell}/r).$$

priority protocol, it requires more satellite channels than reservation-assignment systems with priority protocol. Since difference in hardware cost and complexity is small, it is clear that polled assignment is not competitive with reservation assignment for GMF traffic. We will, therefore, retain only reservation assignment with priority protocol for costing and further analysis. The best of the assignment systems, reservation assignment with priority protocol, requires 14 satellite channels for GMF traffic.

Thus, for both FLTOPS and GMF, reservation-assignment systems are far superior to fixed-, polled-, and random-assignment systems and are the only systems which will be retained for costing. In most cases, the use of priority protocol significantly increases the efficiency of utilization of the satellite channels.

Table 7-14. FLTOPS Large-Ship Reservation-Assignment Channel Requirements Calculation.

SYSTEM TYPE	NUMBER OF CHANNELS REQUIRED	TOTAL MESSAGE GENERATION RATE PER CHANNEL	NUMBER OF ORDERWIRE SLOTS PER FRAME	NUMBER OF MESSAGE BLOCKS PER FRAME	MEAN NUMBER OF RESERVATIONS PER ORDERWIRE SLOT	PROBABILITY REQUEST IS BLOCKED	GOVERNING PRIORITY CLASS	FRAME DURATION IN SECONDS	MEAN MESSAGE WAITING TIME IN SECONDS	PROBABILITY OF EXCESS WAITING TIME
	S	λ'	C	M	P_1	$(1 - P_{oK})$	n	F	$\overline{W}_n$	$P(w > t_n)$
TDMA ORDERWIRE										
Without priority	2	0.362	8	16	-	-	1	2.80	3.24	2.0×10^{-4}
With priority	2	0.362	8	16	-	-	1	2.80	1.49	1.0×10^{-8}
SLOTTED ALOHA ORDERWIRE										
Without priority	2	0.362	8	8	0.066	0.035	1	1.45	3.50	2.6×10^{-4}
With priority	2	0.362	8	8	0.066	0.035	1	1.45	1.54	7.3×10^{-9}

a_2 = 120 bits a_1 = 120 bits b = 1500 bits $\overline{\ell}$ = 12000 bits r = 9600 b/s λ_T' = 0.725 $\overline{m}$ = 8.51

Table 7-15. FLTOPS Medium-Plus Small-Ship Reservation Assignment Channel Requirements Calculations.

SYSTEM TYPE	NUMBER OF CHANNELS REQUIRED	TOTAL MESSAGE GENERATION RATE PER CHANNEL	NUMBER OF ORDERWIRE SLOTS PER FRAME	NUMBER OF MESSAGE BLOCKS PER FRAME	MEAN NUMBER OF RESERVATIONS PER ORDERWIRE SLOT	PROBABILITY REQUEST IS BLOCKED	GOVERNING PRIORITY CLASS	FRAME DURATION IN SECONDS	MEAN MESSAGE WAITING TIME IN SECONDS	PROBABILITY OF EXCESS WAITING TIME
	S	λ'	C	M	P_1	$(1 - P_{oK})$	n	F	$\overline{W}_n$	$P(w > t_n)$
TDMA ORDERWIRE										
Without priority	2	0.217	256	64	-	-	1	14.00	3.13	1.8×10^{-3}
With priority	1	0.435	256	128	-	-	1	24.8	1.65	5.2×10^{-3}
SLOTTED ALOHA ORDERWIRE										
Without priority	1	0.435	8	8	0.079	0.042	1	1.45	4.69	2.1×10^{-3}
With priority	1	0.435	8	8	0.079	0.042	1	1.45	1.54	7.4×10^{-9}

a_2 = 120 bits a_1 = 120 bits b = 1500 bits $\overline{l}$ = 12000 bits r = 9600 b/s λ_T' = 0.435 $\overline{m}$ = 8.51

Table 7-16. FLTOPS Large-, Medium-, and Small-Ships Reservation Assignment Channel Requirements Calculation.

SYSTEM TYPE	NUMBER OF CHANNELS REQUIRED	TOTAL MESSAGE GENERATION RATE PER CHANNEL	NUMBER OF ORDERWIRE SLOTS PER FRAME	NUMBER OF MESSAGE BLOCKS PER FRAME	MEAN NUMBER OF RESERVATIONS PER ORDERWIRE SLOT	PROBABILITY REQUEST IS BLOCKED	GOVERNING PRIORITY CLASS	FRAME DURATION IN SECONDS	MEAN MESSAGE WAITING TIME IN SECONDS	PROBABILITY OF EXCESS WAITING TIME
	S	λ'	C	M	P_1	$(1 - P_{oK})$	n	F	$\overline{W}_n$	$P(w > t_n)$
<u>TDMA ORDERWIRE</u>										
Without priority	4	0.29	256	64	-	-	1	14.00	4.05	6.9×10^{-3}
With priority	2	0.58	256	128	-	-	1	24.8	1.65	5.2×10^{-3}
<u>SLOTTED ALOHA ORDERWIRE</u>										
Without priority	3	0.39	8	8	0.070	0.037	1	1.45	3.82	5.2×10^{-4}
With priority	2	0.58	8	8	0.105	0.058	1	1.45	1.54	7.6×10^{-9}

$a_2 = 120$ bits $\quad a_1 = 120$ bits $\quad b = 1500$ bits $\quad \overline{\ell} = 12000$ bits $\quad r = 9600$ b/s $\quad \lambda_T' = 1.16 \quad \overline{m} = 8.51$

Table 7-17. GMF Polled-Assignment Channel Requirements Calculation.

NO. OF TERMINALS ON SINGLE SATELLITE CHANNEL, N	BUSY-HOUR MESSAGE GENERATION RATE, λ_T'	UTILIZATION, ρ	MAXIMUM ALLOWABLE MESSAGE GENERATION RATE, λ	COMMENT
210	3.08			
53	0.77			
27	0.385	0.4843	0.1423	$\lambda_T' > \lambda$ N.G.
14	0.1925	0.6103	0.1793	$\lambda_T' > \lambda$ N.G.
13	0.1812	0.6199	0.1821	$\lambda_T' > \lambda$ N.G.
12	0.1711	0.6296	0.1849	$\lambda_T' < \lambda$ O.K.

Note: Can handle 12 terminals per channel; therefore, 18 channels are required.

$W_{m2} = 60$ s; $\bar{\ell} = 8{,}170$ bits; $r = 2{,}400$ b/s; $1/2(d/\bar{\ell}) = 0.0367$;

$P_m = 0.01$; $d = 600$; $\bar{\ell}/r = 3.4$; $K = 0.833$; $\lambda_T = 3.7$; $\lambda_T' = K\lambda_T = 3.08$;

$\overline{W} = -W_{m2}/\ell n(P_m) = 13.029$; $\overline{W}/\bar{\ell}/r) = 3.83$; $\lambda = \rho/(\bar{\ell}/r)$;

$$\rho = \frac{\overline{W}/(\bar{\ell}/r) - 1 - \frac{1}{2}(d/\bar{\ell})\,N}{\overline{W}/(\bar{\ell}/r) - \frac{1}{2}(d/\bar{\ell})}.$$

Table 7-18. GMF Reservation-Assignment Channel Requirements Calculation.

SYSTEM TYPE	NUMBER OF CHANNELS REQUIRED	TOTAL MESSAGE GENERATION RATE PER CHANNEL	NUMBER OF ORDERWIRE SLOTS PER FRAME	NUMBER OF MESSAGE BLOCKS PER FRAME	MEAN NUMBER OF RESERVATIONS PER ORDERWIRE SLOT	PROBABILITY REQUEST IS BLOCKED	GOVERNING PRIORITY CLASS	FRAME DURATION IN SECONDS	MEAN MESSAGE WAITING TIME IN SECONDS	PROBABILITY OF EXCESS WAITING TIME
	S	λ'	C	M	P_1	$(1 - P_{oK})$	n	F	$\overline{w}_n$	$P(w > t_n)$
TDMA ORDERWIRE										
Without priority	21	0.147	10	18	-	-	2	12.65	10.87	8.3×10^{-3}
With priority	14	0.220	16	16	-	-	2	11.60	4.44	8.3×10^{-6}
SLOTTED ALOHA ORDERWIRE										
Without priority	20	0.154	8	16	0.216	0.037	2	11.20	11.68	8.6×10^{-3}
With priority	14	0.220	8	8	0.159	0.094	2	5.8	4.32	2.4×10^{-6}

a_2 = 120 bits a_1 = 120 bits b = 1500 bits $\overline{\ell}$ = 8170 bits r = 2400 b/s λ_T' = 3.08 $\overline{m}$ = 5.96

7.2.2 Frequency-Assignment-Availability Requirement

The frequency-management evaluation criterion used in evaluating the DA candidates is defined in section 2 as the frequency-assignment-availability requirement,

> F = the fraction of the frequency assignments comprising a specified bandwidth that must be available for assignment, such that the probability of obtaining the number of assignments needed by the DA candidate to serve the user model traffic is 0.5.

The congestion in the UHF band makes it difficult to obtain the worldwide frequency clearances (frequency assignments) that are highly desirable for military applications. In many operational areas it is not likely that approval would be obtained for using all of the FLTSAT channels. In some areas only 2 or 3 of the 9 channels may be available throughout the entire area. The total number of 25-kHz equivalent-capacity UHF satellite channels is limited to about 14.* The GMF UHF requirement is for at least 14 25-kHz channels (2400 b/s/channel) with any DA candidate. In this analysis it is assumed that there are a total of 14 assignments for which use-approval can be requested. The FLTSAT transponders are fixed-frequency channelized at 25-kHz bandwidth each.

Because of channelization, wide-band TDMA is eliminated as a candidate. The remaining UHF DA candidates for the FLTOPS and GMF user models are DAMA reservation assignment with either TDMA or slotted ALOHA orderwire. The DA performances of the two candidates are essentially identical over the range of interest from frequency-management considerations.

The DA performance curves presented in sections 5 and 7 and appendix B are expressed in terms of a variable number of terminals served. Of interest in the frequency-management considerations is a fixed number of terminals with a variable amount of capacity available to serve a correspondingly variable traffic intensity, dependent upon the number of assignments available. In addition, there is a wide variation in traffic intensity among UHF FLTOPS terminal types. Therefore, for expediency in analysis, the average DA efficiency of information bits per bit transmitted is approximated as 0.92 for the DA candidates applied to the FLTOPS users and 0.90 for the GMF model. Considering the appropriate link models, the effective capacity is 8832 b/s per 25-kHz channel in the FLTOPS network and 2160 b/s per 25-kHz channel in the GMF network.**

Since the transponders are channelized and store-and-forward traffic is specified by the user models, the only DA candidates considered are DAMA reservation-FDMA types. As previously stated, the performances of the two candidates with different orderwire schemes are essentially the same, in view of the assumptions made.

Figures 7-3 and 7-4 present the results of applying the DAMA-FDMA equations from table 2-1 to the UHF FLTOPS and GMF user models respectively. Shown in each figure is the satellite network capacity as a function of the terrestrial-system spectrum usage satisfying

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*The total of 14 channels is composed of 9 FLTSAT 25-kHz channels and an assumed quantity of 4 or 5 FDMA 25-kHz channels spaced through the 500-kHz GAPSAT transponder bandwidth. The assumed GAPSAT quantity is possible from bandwidth and intermodulation considerations, but power limitations may likely restrict the quantity to a lesser value.

**In paragraph 4.3.1 the transmission rate per 25-kHz is given as 9.6 kb/s for the FLTOPS network and 2.4 kb/s for the GMF network. Thus, applying the stated efficiencies, the effective capacities are the values presented, 8832 and 2160 b/s, respectively.

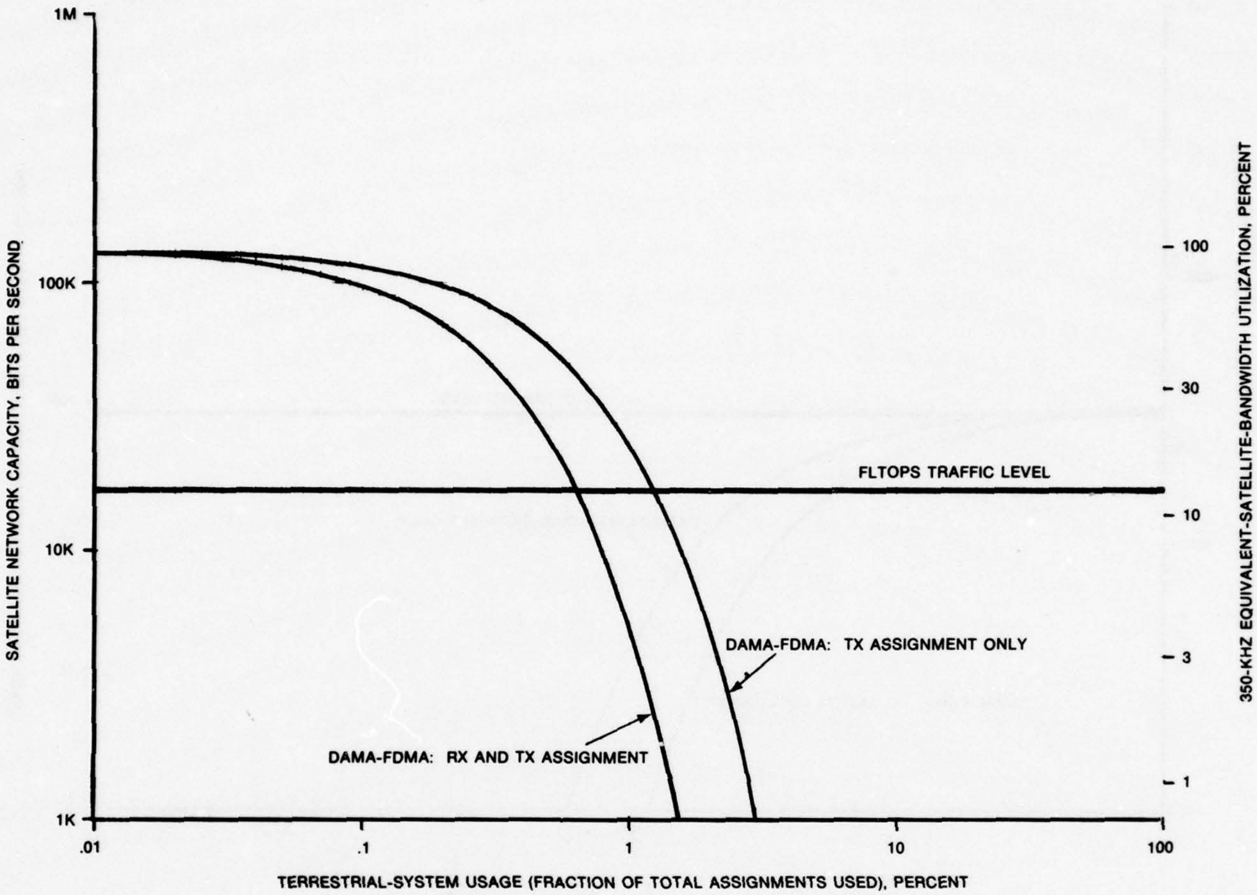

Figure 7-3. UHF Network Capacity Versus Terrestrial Usage for 160 Earth Terminals (FLTOPS).

the 0.5 probability of successful assignments, for the user model parameters listed in table 4-16. The values are calculated for a total of 14 25-kHz assignments. A significant factor for the UHF models is the large number of earth terminals: 160 for FLTOPS and 210 for GMF.

Curves are shown both for the "transmit-assignment only" case and the "receive- and transmit-assignments" case. Also shown in each figure is the network traffic level for the applicable user model. The intersection of this line with the DA system curve defines the maximum allowable fraction of assignments in use, q. From this amount the frequency-assignment-availability requirement, F, is calculated by

$$F = 1 - q . \tag{7-33}$$

The resultant values for F are listed in table 7-19 for the two DA candidates applied to the UHF user models. Identical values are shown for both candidates, based on the assumptions already stated.

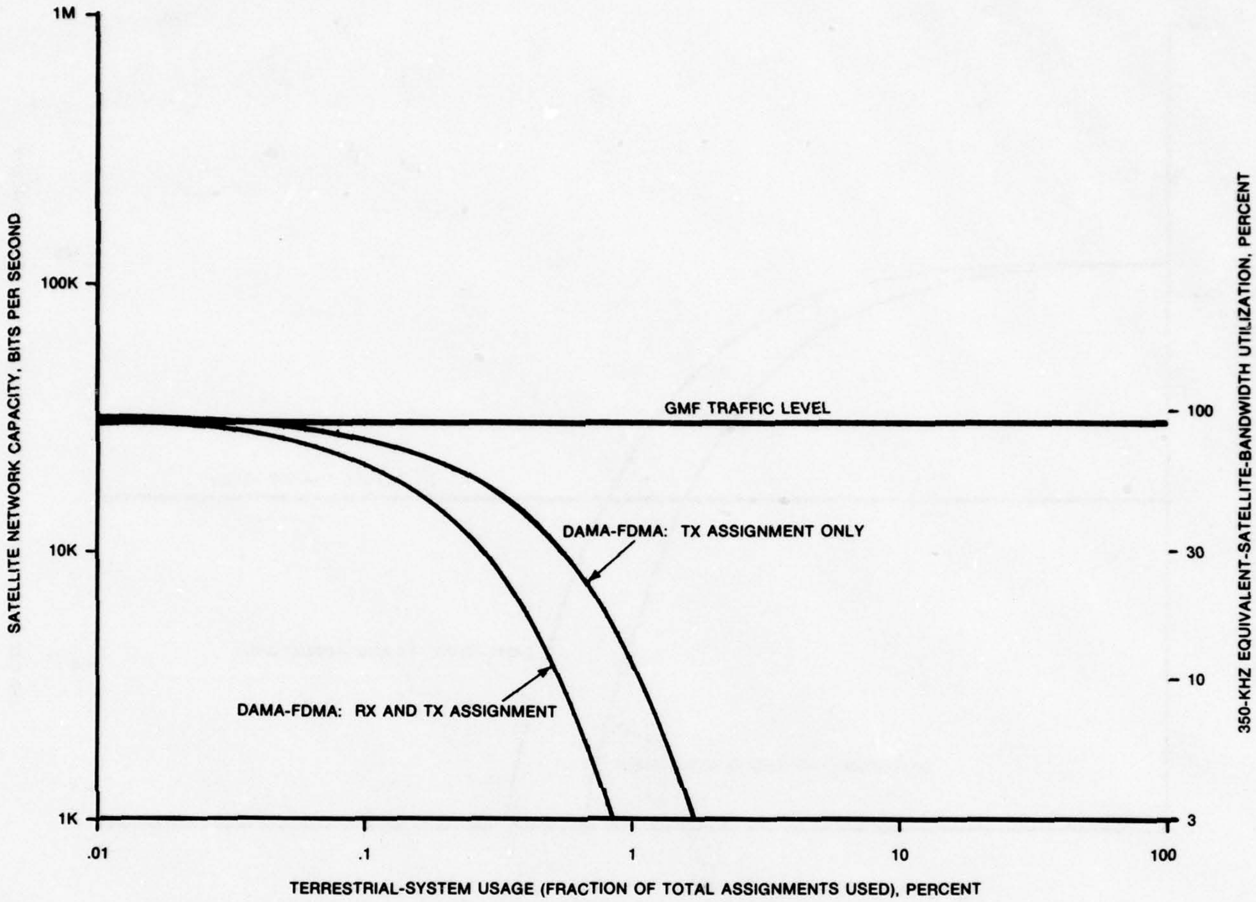

Figure 7-4. UHF Network Capacity Versus Terrestrial Usage for 210 Earth Terminals (GMF).

It should be noted that the traffic capacity axis for figures 7-3 and 7-4 is also representative of the efficiency of satellite-bandwidth resource utilization, as shown on the right-hand ordinate axis. A utilization efficiency of 100 percent is taken as the traffic level served by the DA system using all 14 of the 25-kHz channels assumed (350-kHz equivalent-bandwidth total).* The right-hand axis can be used with the curve to determine the potential utilization efficiency for a specific fraction of assignments in use.

*For the transmission rate per channel applicable to the user network, that is, 9600 b/s for FLTOPS and 2400 b/s for GMF.

Table 7-19. Required Fraction of Frequency Assignments Available, F.

(For user model traffic level and terminal quantity, considering 350-kHz equivalent transponder bandwidth (14 25-kHz channels). For 50 percent probability of obtaining all required assignments.)

DA CANDIDATE	FLTOPS		GMF	
	RX & TX	TX ONLY	RX & TX	TX ONLY
DAMA-FDMA Reservation with TDMA OW	0.994	0.988	0.9998	0.9997
DAMA-FDMA Reservation with slotted ALOHA OW	0.994	0.988	0.9998	0.9997

7.2.3 UHF DA System Cost

One of the most important criteria for evaluating the different demand-assignment techniques is the total system cost. Before the cost can be determined, each candidate must be designed and laid out in sufficient detail to yield accurate system definitions. The approach of this section is to present the designs of the highest ranked demand-assignment candidates for UHF store-and-forward data by providing a detailed block diagram for each candidate along with an explanation of system operation and unit costs. The following candidates are evaluated in this section:

a. DAMA Reservation Assignment - Fixed assignment (TDMA) OW with priority.
b. DAMA Reservation Assignment - Random assignment OW with priority.

7.2.3.1 System Design

Figure 7-5 presents the block diagram of the UHF DAMA reservation-assignment equipment. The same block diagram is valid for both final candidates (TDMA OW and random assignment OW). The difference between the candidates is only in the software implementation of the integral processor. Each candidate utilizes TDMA to subdivide the 25-kHz channels provided by the satellite. It is only in the assignment technique used for the subslots in the orderwire slot of the data frame where the two candidates differ. A single demand-assignment processor is capable of interfacing with up to five modem units. However, in figure 7-5, only one modem unit is shown in detail along with its internal modules. Each modem unit can interface with up to four I/O channels and one OW channel.

The heart of the modem unit is the modem controller. The controller provides the timing and sequencing of traffic between the demand-assignment processor, the TDMA mux/demux and I/O buffer, the modulator/encoder, and the demodulator/decoder. The modulator/encoder take the TDMA data from the TDMA mux/demux and convert it into an rf carrier at a nominal 70 MHz. It is under control of the modem controller. The demodulator/decoder does exactly the inverse function. The TDMA mux/demux module takes the OW, the timing and control information, and the input data and produces a single line of TDMA data which is fed to the

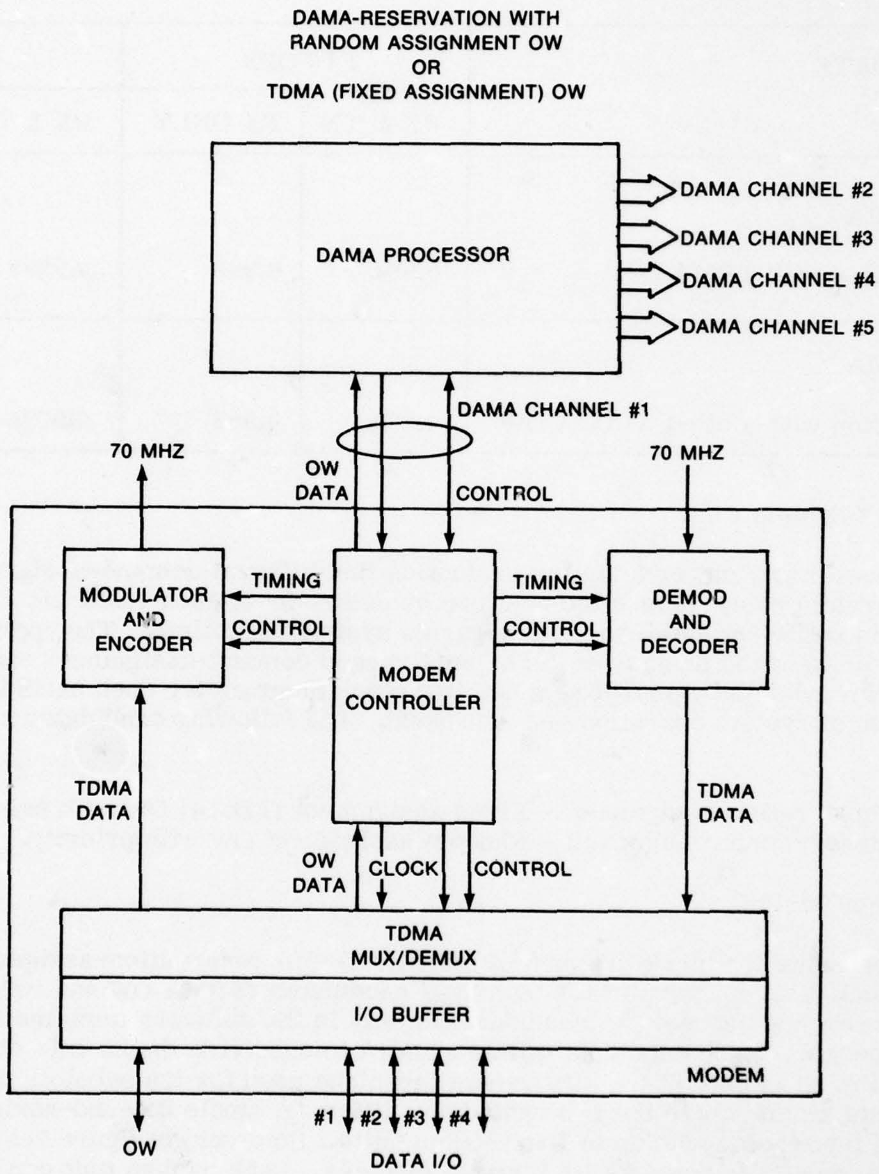

Figure 7-5. DAMA Reservation With Random-Assignment OW or TDMA (Fixed-Assignment) OW.

modulator/encoder. Similarly, it accepts TDMA data from the demodulator and converts it to output data and control information.

7.2.3.2 System Cost

To derive total system cost, it is necessary to identify and price each individual unit or module that comprises the demand-assignment candidate. Then, by applying the UHF user model information concerning the number of network members and the individual channel requirements of each network member, the amount of equipment required by each user can be determined and a total system cost developed. The cost developed in this report does not constitute a formal cost presentation. Rather, they are rough order of magnitude costs, which are intended to provide a reasonable basis for cost comparison only. No other use or application of these costs is intended nor should any be inferred.

7.2.3.2.1 Individual Unit Prices

7.2.3.2.1.1 Demand-Assignment Processor

The demand-assignment processor can be implemented using a microprocessor with 8 kilobytes of memory. The cost of such a unit is estimated to be $12,500. This unit performs the bulk of the system's processing, net control, and message switching. The different OW systems simply require different programs. To implement a system using priority will involve adding an additional 8 kilobytes of memory to accommodate the needed storage. The additional cost is estimated to be $1,000. The estimated parts count is 1,600 pieces, and the estimated MTBF is 1,000 hours.

7.2.3.2.1.2 Modem Unit

Each system may contain one or more modem units. This modem unit is composed of a controller, modulator/encoder, demodulator/decoder, TDMA mux/demux, and an I/O buffer.

The modem controller provides all necessary TDM loop synchronization functions and is estimated to cost $9,000. The MTBF is estimated to be 6,000 hours, and the estimated parts count is 1,500 pieces.

The modulator/encoder and the demodulator/decoder combined is estimated to cost $15,000. The MTBF is estimated to be 7,000 hours, and the estimated parts count is 1,100 pieces.

The TDMA mux/demux provides serial-to-parallel and parallel-to-serial data conversions in order to multiplex/demultiplex several data channels into a single channel and vice versa. The estimated cost is $1,100. The MTBF is estimated to be 40,000 hours, and the estimated parts count is 220 pieces.

The I/O buffer is the interface between the TDMA mux/demux and the external data lines. It consists of line drivers, line receivers, and latches. The estimated cost is $1,100. The MTBF is estimated to be 40,000 hours, and the estimated parts count is 220 pieces.

Using the module data, the modem unit cost is $26,200. The MTBF is 2,780 hours. The parts count is 3,040 pieces.

7.2.3.2.2 Total System Cost

The hardware described above can be used by both UHF user communities. From table 4-16, the FLTOPS user model consists of 160 terminals, 10 large ships, 50 medium ships, and 100

small ships. From the Naval Architecture document referenced in section 4, large and medium ships require 3 channels each and small ships require a single channel. Similarly, table 4-16 indicates that the GMF consists of 210 single-channel terminals. Table 7-20 summarizes the total equipment complement for each user community and table 7-21 summarizes the total system cost. This table indicates that the total cost of demand-assignment for FLTOPS is $9,496,000 and for the Army GMF is $8,337,000.

Table 7-20. User Equipment Complement.

ITEM	DA PROCESSOR	PRIORITY OPTION	MODEM UNIT
FLTOPS			
Large ships	10	10	30
Medium ships	50	50	150
Small ships	100	100	100
GMF	210	210	210

Table 7-21. Total Equipment Cost.

ITEM	FLTOPS				
	UNIT COST	LARGE SHIPS	MEDIUM SHIPS	SMALL SHIPS	TOTAL
DA processor	$12,500	$125,000	$ 625,000	$1,250,000	$2,000,000
Priority option	$ 1,000	$ 10,000	$ 50,000	$ 100,000	$ 160,000
Modem unit	$26,200	$786,000	$3,930,000	$2,620,000	$7,336,000
Total		$921,000	$4,605,000	$3,970,000	$9,496,000

ITEM	GMF	
	UNIT COST	SINGLE-CHANNEL TERMINAL
DA processor	$12,500	$2,625,000
Priority option	$ 1,000	$ 210,000
Modem unit	$26,200	$5,502,000
Total		$8,337,000

7.2.4 UHF Recommendations

The results of applying all the evaluation criteria (S, F, and C) are summarized in table 7-22 based on the data listed in tables 7-11, 7-19, and 7-21. Inspection of the table reveals that in all cases, the use of priority protocol reduces the number of satellite channels required to handle the traffic by one-third to one-half. Further, the use of priority protocol has no effect on the frequency-assignment availability factor, F, and only raises the DA system cost by $160,000 for FLTOPS and by $210,000 for GMF. Clearly the chosen UHF DA candidate should include priority protocol.

The choice between orderwire techniques is not nearly as clear cut. Both fixed-assignment TDMA and random-assignment using slotted ALOHA have identical cost and require the same frequency-assignment availability. Even the required number of satellite channels is the same. However, if the required number of satellite channels, S, was not rounded off to an integer value, the use of a slotted ALOHA orderwire would appear to be slightly better. Assuming that orderwire overload cannot occur because of proper design margins, the use of a slotted ALOHA orderwire is by far the most flexible in handling a mix of high- and low-traffic terminals and in allowing for wide changes in the number and type of terminals in the network. Although the use of a TDMA orderwire avoids the problem of orderwire overload, it is inherently less flexible in accommodating a dynamic user's needs. Therefore, the following are the first and second-choice UHF DA candidates for both FLTOPS and GMF.

a. DAMA-reservation assignment with a slotted ALOHA orderwire and priority protocol.
b. DAMA-reservation assignment with a fixed assignment TDMA orderwire and priority protocol.

Table 7-22. Summary of Evaluation Criteria Application Results.

CANDIDATE DESCRIPTION			EVALUATION CRITERIA APPLICATION RESULTS							
DA SYSTEM TYPE	ORDERWIRE TYPE	PRIORITY PROTOCOL PROVISION	FLTOPS (ALL SHIP COMBINED)				GMF			
			S	F		*C	S	F		*C
				RX & TX	TX ONLY			TX & RX	TX ONLY	
DAMA Reservation	TDMA	No	4	0.994	0.988	9.3	21	0.9998	0.9997	8.1
	TDMA	Yes	2	0.994	0.988	9.5	14	0.9998	0.9997	8.3
	Slotted ALOHA	No	3	0.994	0.988	9.3	20	0.9998	0.9997	8.1
	Slotted ALOHA	Yes	2	0.994	0.988	9.5	14	0.9998	0.9997	8.3

*Estimated production cost in millions of dollars.

7.3 HARDWARE DESCRIPTION OF FINAL UHF CANDIDATE

The final demand-assignment candidate for UHF is DAMA-reservation assignment with priority protocol. In this paragraph we will review the options selected and describe possible hardware and operational protocol that could be used to implement the selected system. All traffic is data traffic and all satellite links within a user community are operated at a single data rate. For FLTOPS the data rate is 9,600 b/s and QPSK modulation would be used. Link, rather than end-to-end, encryption is assumed and the landline interface is assumed to be external to the satellite terminal. All data will be handled as store-and-forward traffic with priority protocol. The DAMA-reservation system consists of fixed-length information time slots and fixed-length orderwire time slots, which are time division multiple accessed. The information time slots are approximately 1,820 bits long and allow 20 bits for guard time, 100 bits for preamble, and 1,700 bits of message. The preamble includes 20 bits for carrier sync, 20 bits for bit sync, 20 bits for packet sync, and 40 bits for packet control including the destination address. Each orderwire time slot is 120 bits long and allows 20 bits for guard time, 20 bits for carrier sync, 20 bits for bit sync, 20 bits for packet sync, and 40 bits of orderwire information.

A block diagram of the hardware implementation is shown in figure 7-5. The incoming messages are stored in a message buffer to await transmission. Each message contains all required header data, including origin, destination, and priority, and is not encrypted. When a new message enters the buffer, the demand-assignment processor is informed of the origin, destination, priority, length, and storage location. The demand-assignment processor forms a list of messages in the buffer and gives a unique number to each message. The highest priority messages are placed at the head of the list and the lowest priority at the end of the list.

Within a given priority class, the message list is maintained in order of time of arrival. The demand-assignment processor examines this list to see if there are any new messages in queue. If so, the processor prepares an orderwire message requesting the number of information time slots required for that message and gives the message number, priority, and destination of that message. This orderwire message is loaded into the mux/demux unit to await transmission on the next orderwire time slot. At the proper time, the modem controller initiates the transmission of this orderwire message. The data message is encrypted, using the frame and time slot number for crypto sync and is used as the input to the PSK data modulator. The data modulator output drives the transmitter.

The orderwire message is received by the central control station and is entered into the network queuing list. This list is maintained in order-of-message priority and within a given priority class in first-in, first-out order. This list forms the network virtual queue. The central control station transmits the message number and length of message at the head of the virtual queue in the central control time slot immediately prior to the frame in which that message is to be transmitted and removes this message from its queuing list.

When a terminal receives an authorization to transmit a given message number, that message is moved into the mux/demux unit. The modem controller initiates the transmission of this message in the authorized time slots.

The output of the receiver if feeds the PSK data demodulator. The data demodulator obtains carrier, bit, and message sync from the packet preamble and demodulates the packet. This packet is sent to the crypto unit for decryption. Time-of-day crypto sync is maintained by all users on the basis of frame and time slot numbers. The frame numbers are transmitted by the control station in the control time slot. The clear text message is buffered in the I/O buffer for distribution on the output message traffic lines in the case of a data message or for entry into the terminal control processor in the case of a control message.

The data modulator adds the required preamble to each packet. The data demodulator monitors the terminal's own transmissions for round-trip timing and sends this timing data to the modem controller so that transmission will be initiated to arrive at the satellite in the proper time slot.

8.1 DEMAND ASSIGNMENT CONCEPTS

The objective of this study is to identify, investigate, and rank candidate demand-assignment techniques for both SHF and UHF military satellite communications application. Demand assignment (DA) deals with techniques to provide efficient matching between the time-varying user demands for service and the available system capacity. Both types of demand assignment are considered in this study: demand assignment multiple access (DAMA) and baseband demand assignment (BDA). DAMA refers to matching the available rf satellite capacity to the time-varying user needs. A DAMA system involves a demand-assignment technique and a satellite multiple-access technique. BDA refers to matching the available terminal capacity associated with an rf carrier to the time-varying local user needs. A BDA system involves a DA technique and a baseband multiplexing technique. A satellite network may employ DAMA, BDA, or both simultaneously, forming a hybrid BDA/DAMA system.

8.2 EVALUATION CRITERIA

Attention has been given to the development and application of evaluation criteria which include those factors important to the utility of military communication systems. The highest ranked candidates are those demand-assignment techniques that provide an acceptable grade of service to all users in the most cost-effective manner, while providing the optimum utilization of available satellite and spectrum resources. For the DATS study, three evaluation criteria have been utilized to rank and select the candidate demand-assignment techniques:

a. S, the number of satellite channels required to handle the user model traffic with a specified grade of service when utilizing the candidate DA system
b. F, the frequency-assignment (spectrum) availability required to permit handling the traffic when utilizing the candidate DA system
c. C, the cost of the candidate DA system equipment in the quantities required to handle the traffic

The values of S, F, and C have been determined for each practical application of demand-assignment techniques to the user models to determine the best DA technique for each.

8.3 STUDY CONSTRAINTS

The following three major constraints bound the scope of this study:

a. Consider only digital traffic (voice and data).
b. Consider only those terminals which are now in inventory or those that are planned for inventory by the early 1980's.
c. Consider only operational satellites or near-term programmed satellites.

The UHF satellites modeled in this study are FLTSAT and GAPSAT. The SHF satellite modeled in DSCS II. Use of demand assignment has been addressed in this study for the general-purpose users only.

During the course of the study, other limitations imposed so that the emphasis remained with investigating and selecting demand-assignment techniques are as follows:

a. Traffic distributions used for this study were assumed to be Poisson for message arrivals and exponential for holding times. Further, only steady-state traffic conditions were considered.
b. Only link encryption was assumed for communication security. End-to-end encryption, although a goal for all future military communications systems, was not considered because it would eliminate some interesting potential candidates.
c. Traffic flow security was not considered, for the same reason. It was assumed that all routing and header information is link encrypted and that traffic volume can be hidden by decoy.
d. Phase-shift keying without coding was specified as the modulation technique. Simple binary phase-shift keying (BPSK) was assumed for the modulation technique for UHF, because BPSK performance is as good as any other for the UHF links and is somewhat simpler to implement than QPSK. Quaternary phase-shift keying (QPSK) was assumed for SHF, because many of the links are bandwidth limited and QPSK offers a 2:1 bandwidth advantage over BPSK for the same rate.

8.4 DEMAND-ASSIGNMENT USERS

Before demand-assignment systems can be evaluated to determine the optimum system, the demand-assignment users must be identified and described. Information concerning each user's terminal equipment and estimated traffic has been compiled. From this information a model has been constructed for each user which contains all the data required to evaluate DA candidates for that user. The following potential users of demand assignment have been identified for MILSATCOM systems:

a. UHF

   1. US Navy Fleet Operations (FLTOPS)
   2. Ground Mobile Forces (GMF)

b. SHF

   1. US Navy Fleet Operations (FLTOPS)
   2. Ground Mobile Forces (GMF)
   3. Defense Communication System (DCS)

8.5 TECHNICAL DEVELOPMENT

One of the major products of this study is the development, cumulation, and unified presentation of the theory applicable to demand assignment of capacity to users, by various techniques, for several types of traffic statistics. The theory has been applied to the representative user models to provide realistic vehicles for evaluating the demand-assignment system candidates. Presented in this report are the following:

a. The general technical background required for analysis of the various candidates.
b. Comparisons of the merits and shortcomings of various assignment techniques.
c. Frequency-management considerations.
d. Consideration of other system parameters such as communications security, priority protocol, muliplexing, multiple access, and diurnal traffic variations on candidate system performance.

Voice traffic and data traffic with both switched and store-and-forward handling have been considered. Applied in combination with the evaluation criteria, the traffic theory and design concepts presented in this report enable the recommendation of demand-assignment systems for the several user models.

8.6 RECOMMENDED SHF DEMAND-ASSIGNMENT SYSTEMS

The results of applying the satellite-channel requirement, S, the frequency-assignment-availability requirement, F, and the total DA system equipment cost, C, evaluation criteria as presented in section 6, paragraph 6.2, are summarized in table 8-1. Based on these results, the following are the final selected DA candidates for the SHF user models:

a. FLTOPS

   1. DAMA-reservation, using TDMA for satellite multiple access.
   2. DAMA-reservation, using FDMA for satellite multiple access.

b. GMF

   1. BDA-TASI, using FDM for baseband multiplexing and FDMA for satellite multiple access.
   2. DAMA-reservation, using TDMA for satellite multiple access.

c. DCS

   1. BDA-TASI, using FDM for baseband multiplexing and FDMA for satellite multiple access.
   2. BDA-TASI, using TDM for baseband multiplexing and TDMA for satellite multiple access.

For FLTOPS the selected candidates are equal, using all three evaluation criteria. The selection between DAMA-TDMA and DAMA-FDMA will depend on other issues.

For DCS and GMF there is no single optimum choice. The selected candidates require an equal number of satellite channels. BDA-TASI using FDM-FDMA is superior when operating in a congested frequency spectrum while BDA-TASI using TDM-TDMA (DAMA-TDMA for GMF) is considerably less expensive. The final selection process can only be made when the most important evaluation criterion is identified.

Detailed descriptions of the recommended implementations for BDA-TASI and DAMA-TDMA are given in section 6, paragraph 6.3.

8.7 RECOMMENDED UHF DEMAND-ASSIGNMENT SYSTEMS

The results of applying the S, F, and C evaluation criteria as presented in section 7, paragraph 7.2, are summarized in table 8-2. Based on these results, the following are the final selected DA candidates for the UHF user models:

a. FLTOPS and GMF

   1. DAMA-reservation assignment with a slotted-ALOHA orderwire with priority protocol provisions.

Table 8-1. Summary of Evaluation Criteria Application Results for SHF.

CANDIDATE DESCRIPTION			EVALUATION CRITERIA APPLICATION RESULTS											
DA SYSTEM TYPE	MULTIPEX TECHNIQUE	MULTIPLE ACCESS TECHNIQUE	FLTOPS				GMF				DCS			
			S	F		*C	S	F		*C	S	F		*C
				RX & TX	TX ONLY			RX & TX	TX ONLY			RX & TX	TX ONLY	
BDA-	TDM	TDMA	133	0.890	0.780	1.3	2304	0.996	0.992	4.4	1176	0.976	0.952	1.7
Reservation	TDM	FDMA	133	0.820	0.010	4.6	2304	0.974	0.250	40.9	1176	0.903	0.120	16.0
	FDM	FDMA	133	0.820	0.010	2.1	2304	0.974	0.250	23.7	1176	0.903	0.120	11.9
BDA-	TDM	TDMA	122	0.890	0.780	1.4	1302	0.991	0.984	5.8	622	0.952	0.897	2.1
TASI	TDM	FDMA	122	0.810	0.010	4.2	1302	0.965	0.110	36.8	622	0.875	0.050	14.1
	FDM	FDMA	122	0.810	0.010	2.0	1302	0.965	0.110	16.2	622	0.875	0.050	7.5
DAMA-	N/A	TDMA	41	0.890	0.780	1.3	1388	0.994	0.988	4.4	784	0.967	0.939	1.7
Reservation	N/A	FDMA	41	0.890	0.780	2.2	1388	0.985	0.970	25.7	784	0.945	0.897	12.6
DAMA Reservation With VOX	N/A	FDMA	41	0.890	0.780	2.6	1388	0.985	0.970	27.4	784	0.945	0.897	13.4

*Estimated production cost in millions of dollars.

2 DAMA-reservation assignment with a fixed-assignment TDMA orderwire with priority protocol provisions.

For each user model, both selected candidates provide equal service with the same satellite-channel requirements and assignment-availability requirements at approximately equivalent costs. However, DAMA-reservation with a slotted-ALOHA orderwire is ranked higher because of its inherent flexibility to accommodate the dynamic requirements of the UHF using community.

The recommended implementations are described in Section 7, paragraph 7.3.

Table 8-2. Summary of Evaluation Criteria Application Results for UHF.

CANDIDATE DESCRIPTION			EVALUATION CRITERIA APPLICATION RESULTS							
DA SYSTEM TYPE	ORDERWIRE TYPE	PRIORITY PROTOCOL PROVISION	FLTOPS (ALL SHIP COMBINED)				GMF			
			S	F		*C	S	F		*C
				RX & TX	TX ONLY			TX & RX	TX ONLY	
DAMA Reservation	TDMA	No	4	0.994	0.988	9.3	21	0.9998	0.9997	8.1
	TDMA	Yes	2	0.994	0.988	9.5	14	0.9998	0.9997	8.3
	Slotted ALOHA	No	3	0.994	0.988	9.3	20	0.9998	0.9997	8.1
	Slotted ALOHA	Yes	2	0.994	0.988	9.5	14	0.9998	0.9997	8.3

*Estimated production cost in millions of dollars.

A.1 BLOCKING PROBABILITY

For voice traffic, the grade of service is usually specified in terms of the probability that a call being placed will find no idle channels and will therefore be blocked. CCITT (reference 1) recommendation for international trunking circuits is that the blocking probability, B, for a lost-calls-cleared system shall not exceed 1% during busy hour. The number of trunk circuits required to achieve this blocking probability, n, is given by the Erlang B equation and is shown in figure A-1 as a function of the busy-hour traffic offered (A), reference 2. This curve assumes incoming calls are originated from an essentially infinite source population.

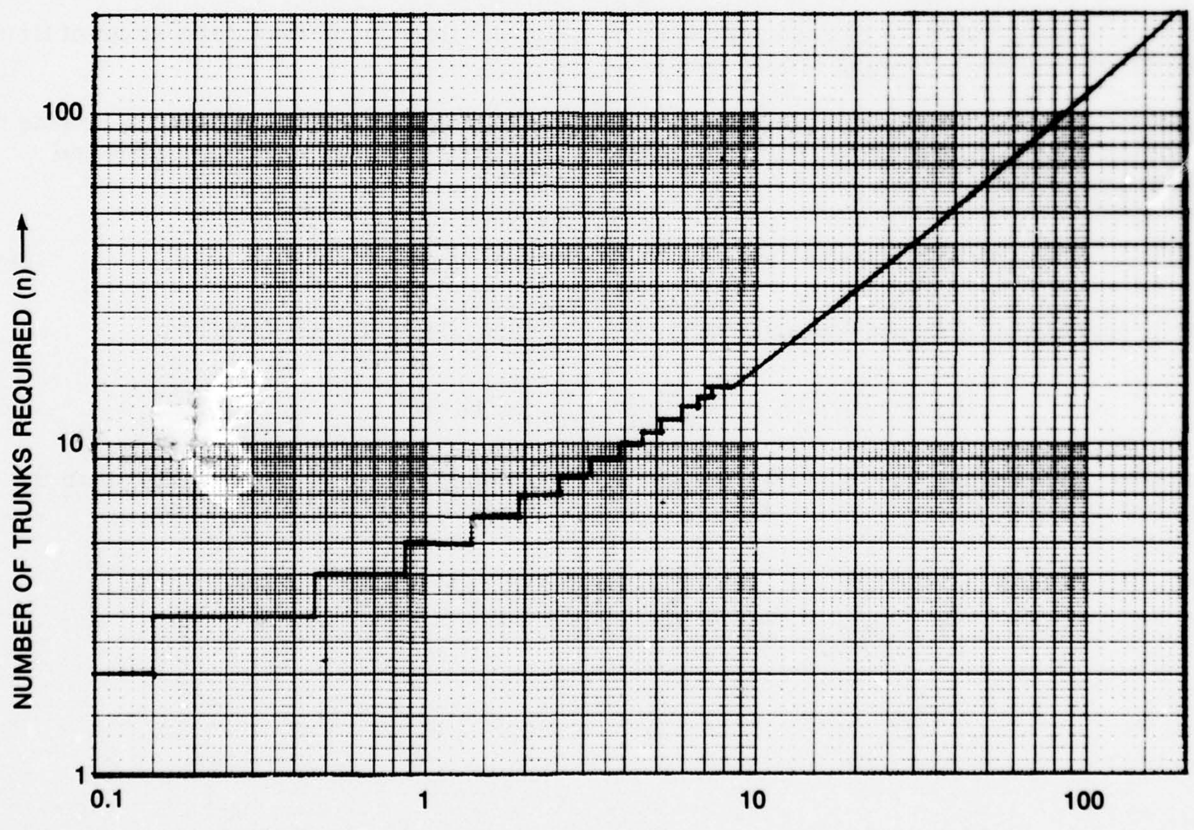

Figure A-1. Minimum Number of Trunks Required for 1% Blocking in a Lost-Calls-Cleared System With an Infinite Number of Sources and Full Availability.

This curve can be used to determine the number of channels or trunks (n) required to provide a blocking probability of 1 percent, given the offered traffic intensity (A). In a baseband demand-assignment system, the offered traffic intensity is for the single terminal, and the number of channels is the number of baseband channels. In demand-assignment multiple access, the offered traffic intensity is the total traffic in the network, and the number of channels is the total number of satellite voice channels required by the network.

A.2 TASI

In a time assignment speech interpolation (TASI) system, a number of trunks are time-shared between a larger number of users (references 3, 4, and 5). If speech sounds have temporarily ceased from one user and speech activity starts from another user without a channel, the channel is reassigned to the active user. This is an extremely dynamic allocation of channels to users having speech activity. The probability, P_j, that exactly j of the n off-hook input lines are active, is given by a binomial distribution or

$$P_j = \frac{n!}{j!(n-j)!}\alpha^j(1-\alpha)^{n-j}, \qquad \text{(A-1)}$$

where α is the probability of speech activity in a channel (ie, the average percentage of time that an off-hook line contains speech sounds).

If there are m output channels, then the number of active input lines which will not be able to obtain an output channel (given that j input lines are active) is j - m, and the conditional freeze-out probability, $P_{f/j}$, for any one of the active lines is

$$P_{f/j} = \frac{j-m}{j} \text{ for } j \geq m. \qquad \text{(A-2)}$$

The probability of a freeze-out and exactly j active input lines, P_{fj}, is therefore

$$P_{fj} = P_{f/j}\, Pj = \frac{j-m}{j}\,\frac{n!}{j!(n-j)!}\alpha^j(1-\alpha)^{n-j} \qquad \text{(A-3)}$$

The total freeze-out probability, P_f, is obtained by summing P_{fj} over all j greater than the number of output channels, m, up to the number of off-hook input lines, n. Then

$$P_f = \sum_{j=m+1}^{n} P_{fj} = \sum_{j=m+1}^{n} \frac{j-m}{j}\,\frac{n!}{j!(n-j)!}\alpha^j(1-\alpha)^{n-j}, \qquad \text{(A-4)}$$

which is the desired result. It has been found that the speech activity probability, α, on long-haul circuits is 0.4 and that satisfactory quality is provided if P_f is less than or equal to 1/2 percent (reference 4). The minimum number of output channels, which will provide a P_f less than or equal to 0.005, can be found by summing equation A-4 in inverse order from j = n downward until the maximum allowable P_f is exceeded. The resultant last value of j is then the minimum number of channels required and is plotted versus n, the number of off-hook users in figure A-2.

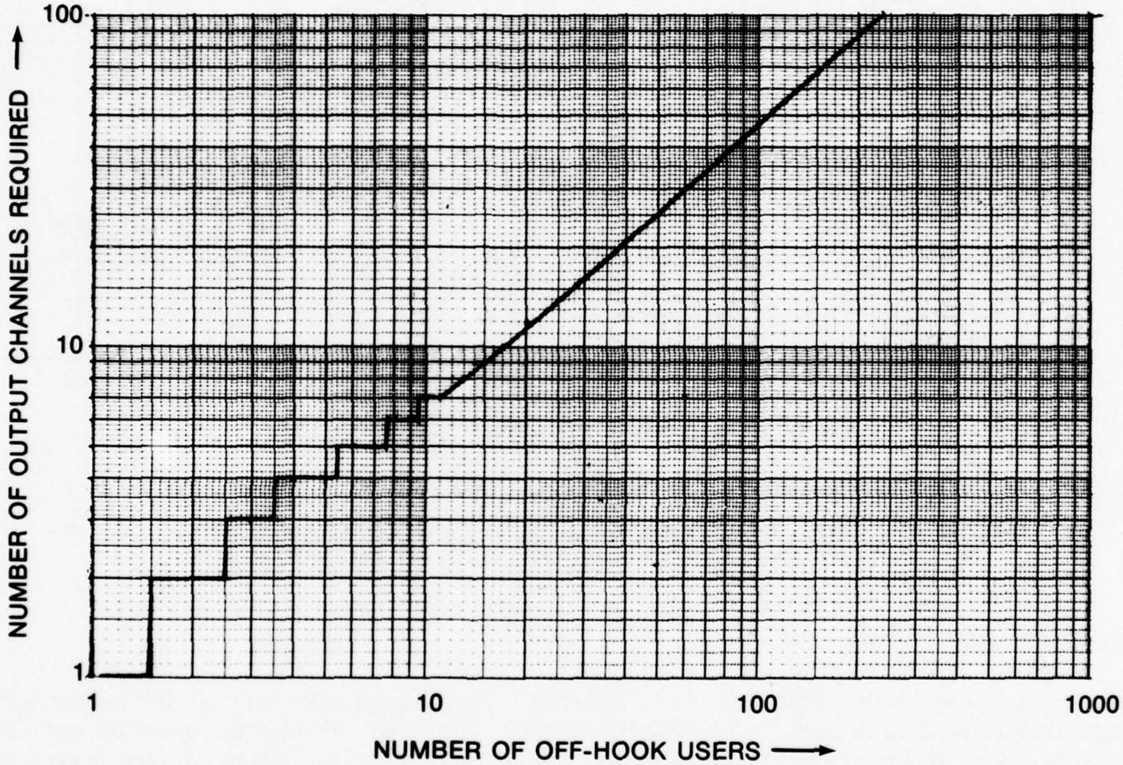

Figure A-2. Number of Channels Required Versus Number of Inputs for a Terminal Using TASI (Assuming 40% Activity and 1/2% Freeze-Out).

The maximum number of off-hook users for a 1 percent blocking probability as a function of busy-hour traffic intensity is given in figure A-1. Now, in order to determine the number of output channels required given the busy-hour traffic intensity, one first determines the number of trunks (n) required for the specified busy-hour traffic intensity from figure A-1. Since the maximum number of off-hook users equals the number of input trunks, one next determines the number of TASI output channels required for the determined number of trunks from figure A-2. This procedure has been carried out using figures A-1 and A-2 and the result is plotted in figure A-3.

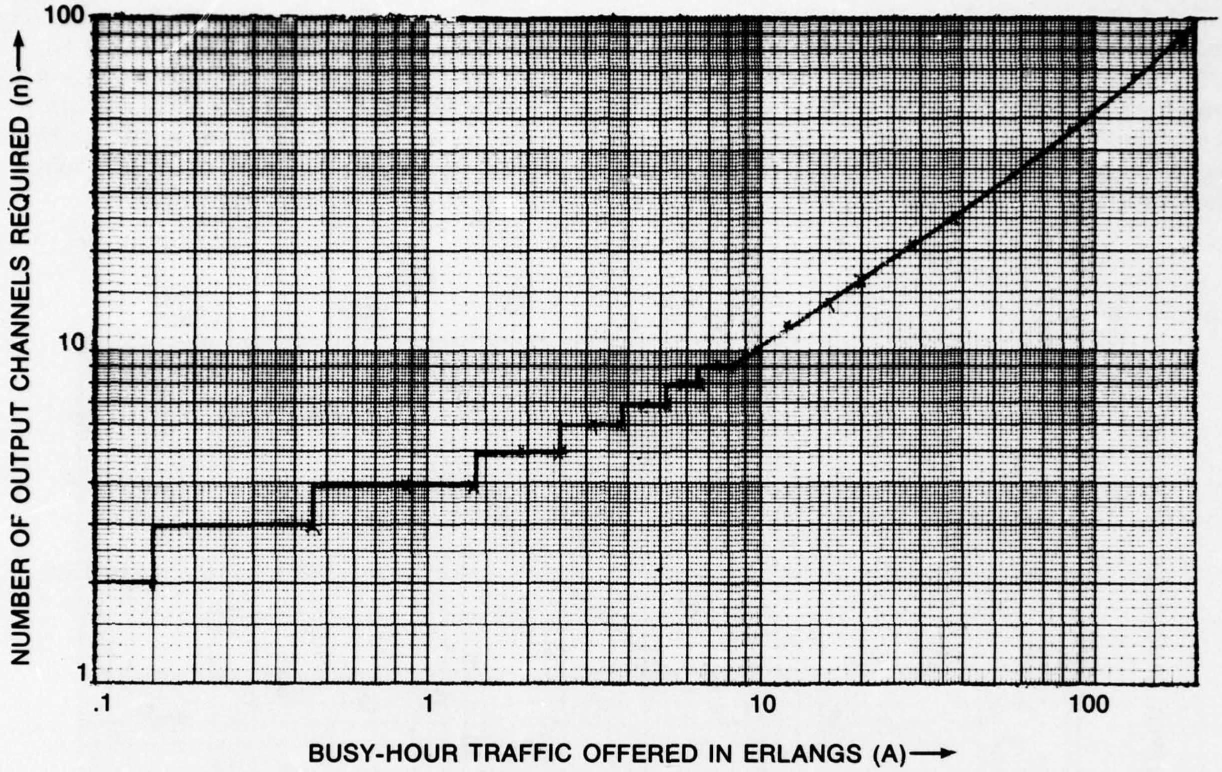

Figure A-3. Number of Output Channels Required for TASI To Give 1/2% Probability of Freeze-Out and a 1% Blocking.

A.3 SPEECH PACKETS

In many digital speech systems, such as slotted ALOHA, it is necessary to divide the speech message into fixed length packets consisting of a preamble of "a" bits followed by "b" information bits. For an exponentially distributed voice spurt of mean length, $\bar{\ell}$, the optimum number of information bits per packet is given by reference 7 as

$$b = \bar{\ell}\sqrt{2a/\bar{\ell}} \quad . \qquad \text{(A-5)}$$

Voice spurts are exponentially distributed with a mean duration of about 1 second (reference 3). Assuming a 16-kb/s delta-modulated voice link and a 120-bit preamble, the optimum value of b is 1,960 bits, and the entire packet length is 2,080 bits.

The mean number of packets per voice spurt, $\overline{m}$, is

$$\overline{m} = \frac{1}{1 - e^{-(b/\bar{\ell})}} . \qquad \text{(A-6)}$$

For our case, $\overline{m}$ is 8.67. The mean voice spurt length in bits is increased from ℓ to $\overline{m}(a+b)$. Correspondingly, the average packet activity factor, α', is increased from the voice activity factor, α , by the ratio $\overline{m}(a+b)/\overline{\ell}$ or

$$\alpha' = \alpha\overline{m}(a + b)/\overline{\ell}, \tag{A-7}$$

where α is the speech activity factor of the analog speech. Assuming an α of 0.40, then for our case, α' is 0.45. Thus, for a packet ALOHA-type system, the packet generation probability for a user is increased to 0.45.

A.4 SLOTTED ALOHA SPEECH TRANSMISSION

In an ALOHA-type system, the time slots could be organized into frames with k slots per frame. An active user could then choose at random any one of the k time slots in the frame for transmitting his speech packet. The probability that a specific active user packet, x, will coincide with a specific active user packet, j, (this is termed "hit by" j) is then given by

$$P\left[(\text{hit by } j)/(j \text{ is active})\right] = 1/k \tag{A-8}$$

The probability that user j packet is active is given by the speech activity probability, α', so that the probability that any given active user will be hit by user j is

$$P(\text{hit by } j) = \alpha'/k. \tag{A-9}$$

It follows that the probability of not being hit by j is

$$P(\text{no hit by } j) = (1 - \alpha'/k). \tag{A-10}$$

The probability of not being hit by any of the other (n - 1) off-hook users or input lines, assuming that each user packet is transmitted q times, is

$$P(\text{no hit}) = (1 - \alpha'/k)\ (n - 1)q. \tag{A-11}$$

So the probability of a hit on-user packet x by some other of the (n - 1) off-hook users is

$$P = (\text{hit on } x) = 1 - P(\text{no hit}) = 1 - (1 - \alpha'/k)\ (n - 1)q. \tag{A-12}$$

In order to freeze out this packet, all q transmissions of this packet must be hit. The probability of freeze-out, h, is therefore given by

$$h = \left[P(\text{hit on } x)\right]^q = \left[1 - (1 - \alpha'/k)^{(n - 1)q}\right]^q. \tag{A-13}$$

It has been found from experience with TASI that a speech loss of 2% still provides adequate voice quality. Assuming h = 0.02 and $\alpha' = 0.45$, the value of q which minimizes the required number of slots per frame, k, is q = 6. Figure A-4 has been plotted for q = 6. As with TASI, the ordinate can be converted from the number of off-hook users to traffic intensity by use of figure A-1. This gives the number of packet slots per frame versus the input traffic intensity required to provide a speech loss of 2% or more for less than 1% of the busy hour as shown in figure A-5.

Since some time slots will not be occupied by any user, the average power will be less than the full-duty-cycle power. The probability that a given time slot in the frame will not be occupied by a given user packet, j, is given in equation A-10. The approximate probability that this time slot will be missed by all potential packets, P_m, is

$$P_m \approx (1 - \alpha'/k)^{nq} \tag{A-14}$$

For our case, with $\alpha' = 0.45$, $q = 6$, and $n = 100$, we have from figure A-4 that $k = 360$ and, therefore, P_m is 0.47. Therefore, the probability that the time slot will be occupied is 0.53, and the average power is 2.8 dB below the power of a 100% active frame.

Figure A-4 gives the required number of packet slots per frame (or required voice channel capacity) as a function of the number of off-hook users. The maximum number of off-hook users which must be accommodated is determined by the busy-hour traffic intensity and the maximum allowable blocking probability, as shown in figure A-1. In order to obtain the required number of voice circuits (k) as a function of the input traffic intensity (A) for a 1-percent blocking probability (B), one first determines the number of input lines (n) required to handle the busy-hour traffic intensity (A) from figure A-1. The maximum number of off-hook users during busy-hour is of course equal to the number of input lines. Therefore, the number of packet slots per frame or voice channels required is obtained from figure A-4 for the number of input lines (n). This procedure was carried out to obtain the required number of packet slots per frame as a function of the busy-hour input traffic intensity and the result is plotted in figure A-5.

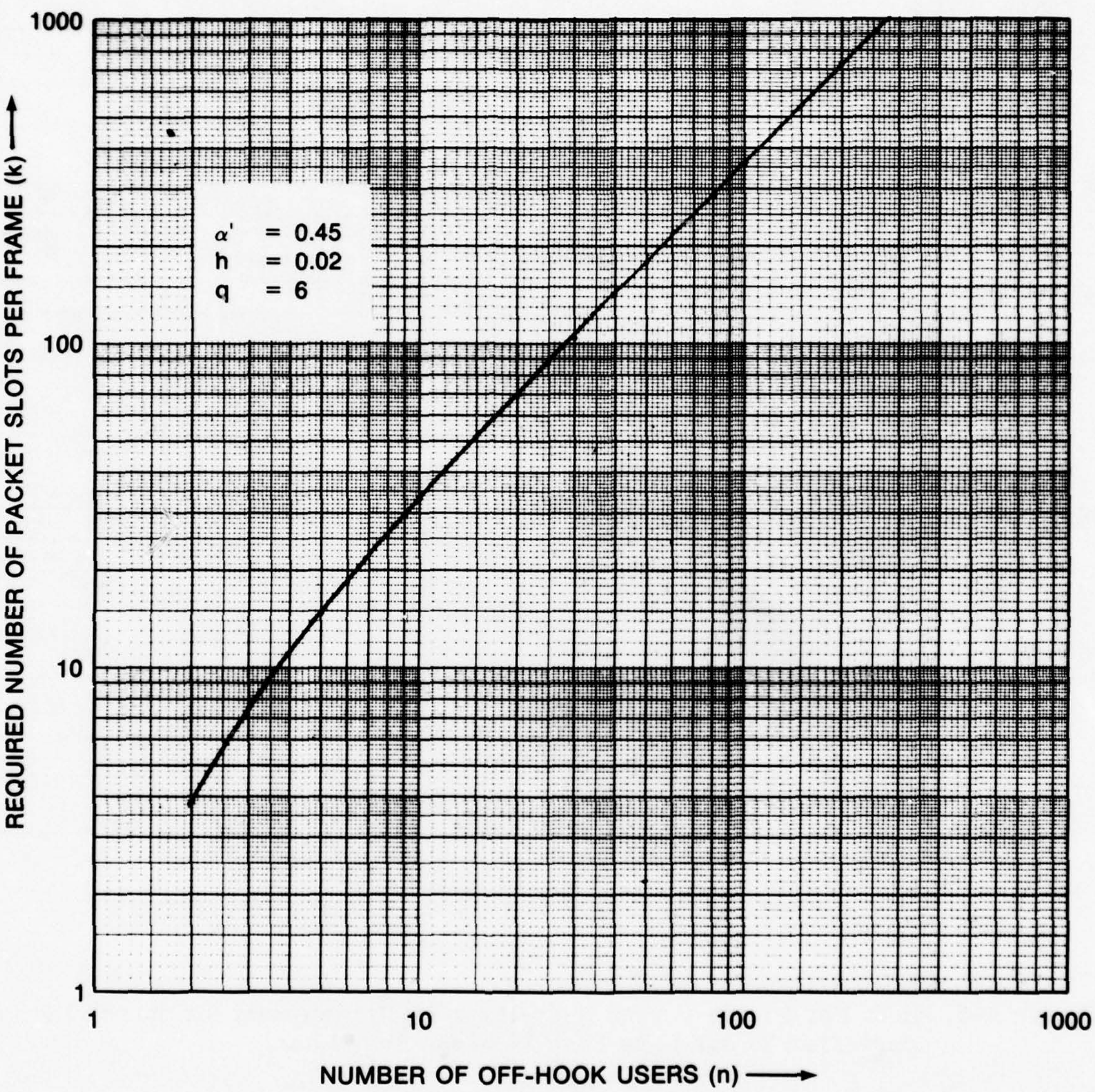

Figure A-4. Slots Per Frame Versus Number of Users for Slotted ALOHA Speech Transmission With 6 Packet Repetitions and 2% Speech Loss.

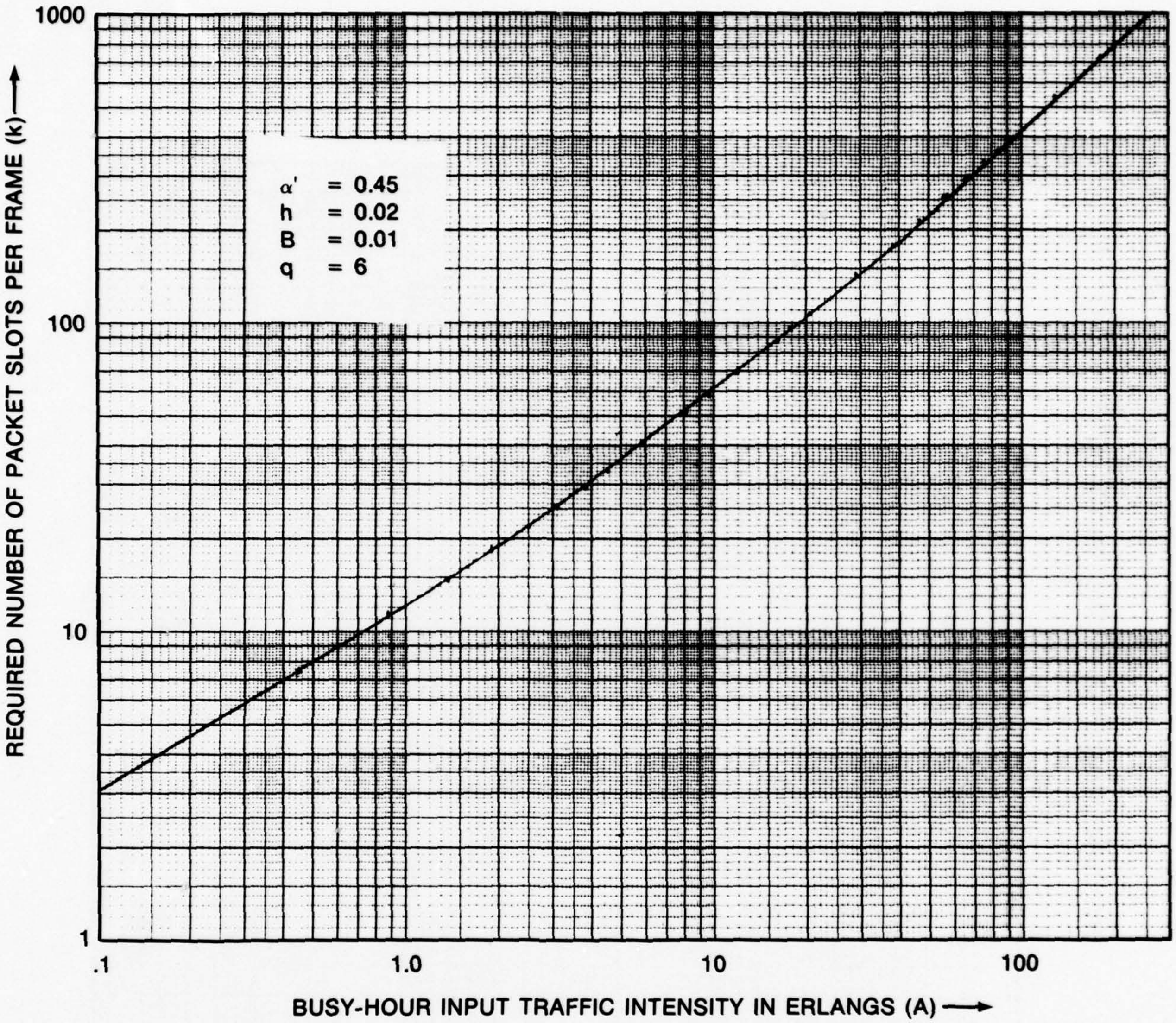

Figure A-5. Slots Per Frame Versus Busy-Hour Traffic Intensity for Speech Loss of More Than 2% for Less Than 1% of the Busy Hour.

A.5 DIURNAL VARIATION OF TRAFFIC INTENSITY

It has been found that local telephone traffic peaks at about 10 am and 4 pm, dips to a low at about 1 pm, and falls to almost zero from 9 pm to 7 am the next day (reference 6). In this report we shall assume that data traffic follows the same diurnal variations as telephone traffic. One must provide a sufficient channel capacity to accommodate these peaks in local traffic intensity. An idealized curve for variations in local traffic intensity is shown in figure A-6. This curve is normalized so as to represent a 24-hour average traffic intensity of one Erlang. It will be noted from this curve that the peak traffic intensity reaches three times the 24-hour average traffic intensity.

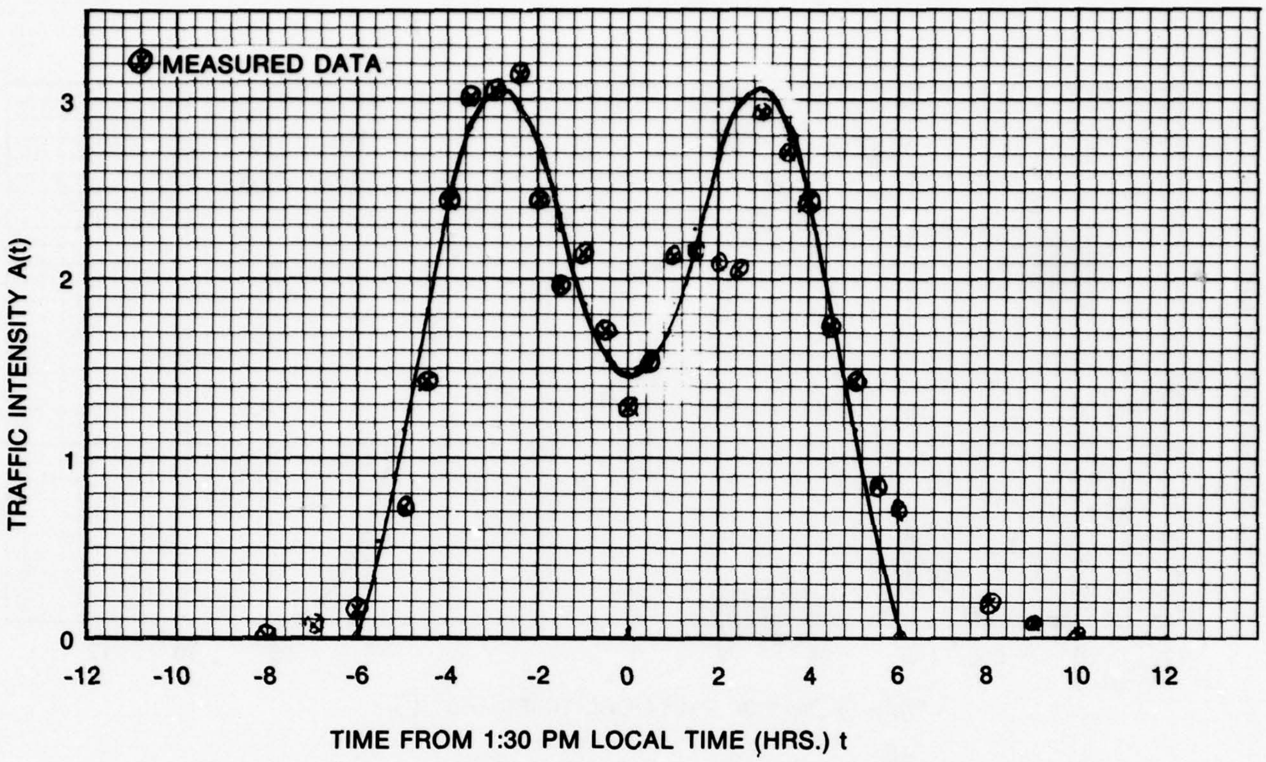

Figure A-6. Time Variation of Traffic Intensity for Local Traffic.

In satellite links, a single satellite may cover a rather wide range of local times. In the important cases of Europe and Continental US, the major users are spread over a local time span of about 3 to 4 hours. If one assumes that the traffic intensity of the individual is as shown in figure A-6 and that the terminals are uniformly distributed over a time span of 4 hours, then the composite traffic intensity will vary as shown in figure A-7. This curve is again normalized so that the 24-hour average traffic intensity is one Erlang. Here it will be noted that the peak traffic intensity exceeds the 24-hour traffic intensity by a factor of 2-1/2.

The peak to average traffic intensities for a single terminal and for a satellite network can be taken from figures A-6 and A-7 as 3 and 2-1/2 respectively.

A.5.1 Local Traffic Intensity Variation

Typical diurnal variations in local traffic intensity are given by Mina (reference 6). The Mina data is shown in figure A-6 along with a plot of the emperical diurnal traffic intensity equation:

$$A(t) = \left\{ \begin{array}{l} \left[1.6 - 0.6 \cos (\pi t/3) - t^4/1296\right]/0.7 \text{ for } -6 \leq t \leq 6 \\ 0 \text{ for } \left|t\right| > 6 \end{array} \right\} \quad \text{(A-15)}$$

where A(t) is the traffic intensity in Erlangs and t is the time in hours from 1:30 pm local time. This equation has been normalized so that the average traffic intensity over a 24-hour period is one Erlang. Note that the peak traffic intensity is three Erlangs or three times the 24-hour average traffic intensity.

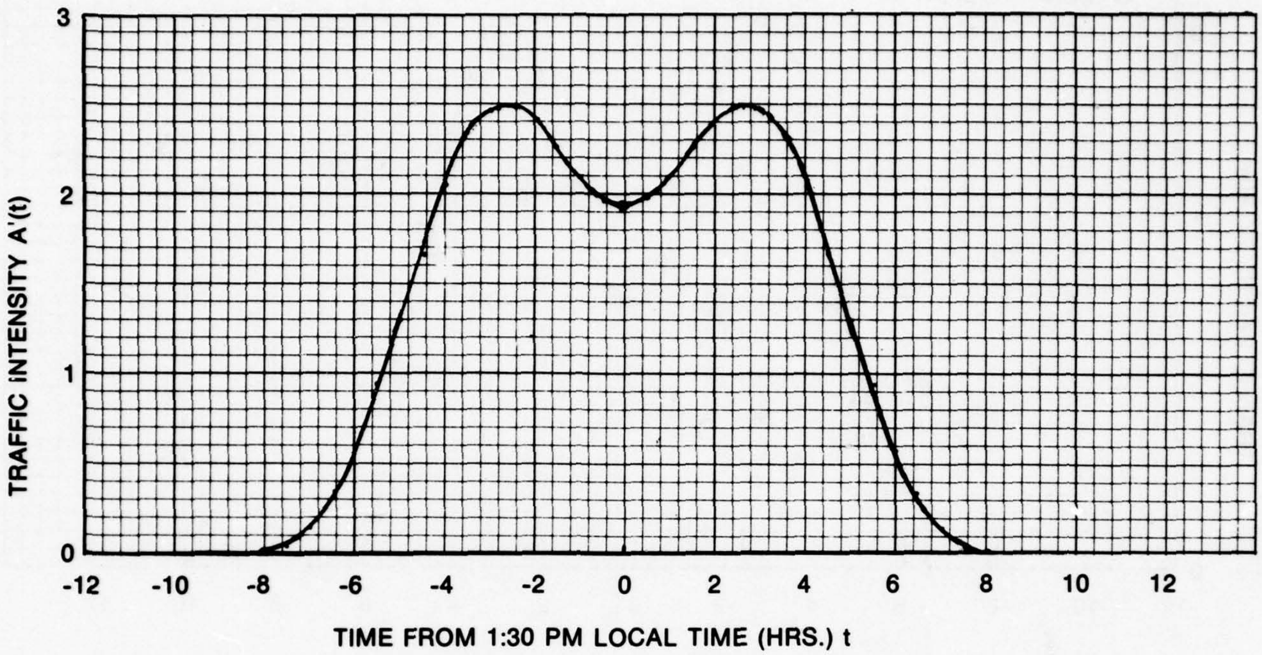

Figure A-7. Time Variation of Traffic Intensity for Terminals Spread Over a Four-Hour Local Time Span.

A.5.2 Traffic Intensity Variations for Networks of Geographically Dispersed Terminals

If the network is geographically dispersed over several time zones and terminals maintain the traffic intensity variations of equation A-15 by local time, then there will be a tendency to smooth out the peak traffic load. If we assume a local time zone spread of plus or minus Δt hours from the geographical center local time, t, and also assume a uniform distribution of terminals over this spread in local time, then the variation in total traffic, A'(t), is given by

$$A'(t) = \frac{1}{2\Delta t} \int_{t - \Delta t}^{t + \Delta t} A(t)\, dt \qquad \text{(A-16)}$$

where A(t) is given by equation A-15. Performing the indicated integration, making allowance for the limited range of the argument of equation A-15, gives

$$A'(t) = \frac{1}{1.4\Delta t} \left[1.6(t_2 - t_1) - \frac{1.8}{\pi} (\sin(t_2 \pi/3) - \sin(t_1\pi/3)) - \frac{t_2^{\,5} - t_1^{\,5}}{6480} \right] \qquad \text{(A-17)}$$

where t_1 and t_2 are given by

$$\left.\begin{aligned} t_1 &= \max\left[-6,\ t - \Delta t\right] \\ t_2 &= \min\left[6,\ t + \Delta t\right] \end{aligned}\right\} \qquad \text{(A-18)}$$

where max[,] and min[,] refer to the maximum and minimum of the arguments enclosed in the brackets.

The results of this integration over a local time span of ±2 hours from the network center is shown in figure A-7. The traffic intensity, A'(t), has again been normalized so that the 24-hour average traffic intensity is one Erlang.

A.6 REFERENCES

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2. Siemens, "Telephone Traffic Theory Tables and Charts," part 1, Siemens Aktiengesellschaft, Berlin, Germany.

3. K. Bullington and J. M. Fraser, "Engineering Aspects of TASI," BSTJ, Vol 38, 1959, pp 353-364.

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B.1 INTRODUCTION

In the communications of record data, such as teletype and tactical data, delays of from several seconds up to many minutes are often tolerable. The efficiency of utilization of the communications facility can be increased by storing messages in a waiting line or queue until the communications capacity to transmit the message is available. Communications systems which store messages in a queue until the capacity to forward them is available are known as store-and-forward systems. Storing of the messages in a queue allows a backlog of messages to be formed so that the communications channel can be kept busy for a large percentage of the time. The efficiency of channel use is thereby increased. If the messages arrive randomly or are of random length, loading of the channel close to its maximum capacity requires a long waiting line or queue. This results in long waiting times. The maximum efficiency which can be achieved in the use of the channel is therefore limited by the waiting time which can be tolerated in the system.

A diagram of a simple queuing system is shown in figure B-1. We will compare various store-and-forward systems as to the amount of traffic they can handle without exceeding a specified maximum mean waiting time, W_{max}, where W is the mean time from the submission of the last bit of a message until the reception of the last bit of the message.

The reader is referred to the available literature for a general mathematical analysis of store-and-forward systems (references 1, 2, 3). Where possible, published mathematical results are adapted to the present analysis, and only the pertinent results are presented in this appendix.

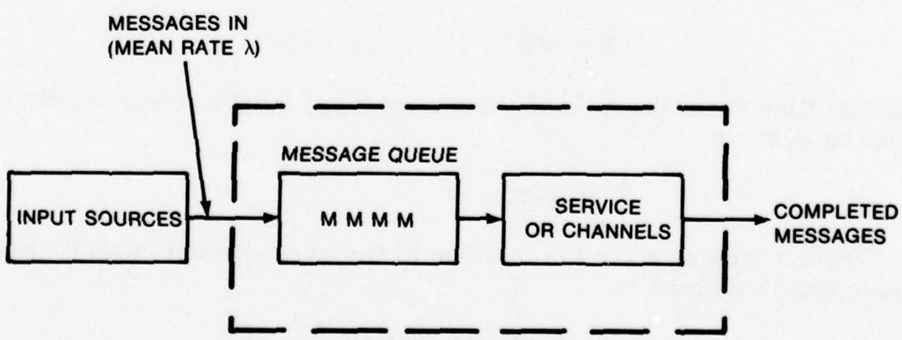


Figure B-1. Single Server Queuing System.

B.2 TYPES OF TRAFFIC

Traffic types will be classified in terms of the message arrival and message length statistics as shown in table B-1. The abbreviated type designation for each type of traffic is shown in the last column where the first letter designates the arrival process and the second letter designates the message length statistics. In this notation, D stands for deterministic or periodic and M stands for Markovian or random. We will consider both periodic and random message arrivals and both fixed and random length messages. Tactical data interchange links (TADIL) often generate periodic, fixed length messages. Orderwire or control channel messages generally have random arrival times with fixed message lengths. Finally, teletypewriter messages generally have both random arrival times and random lengths.

Table B-1. Traffic Statistics for Various Applications.

TYPE OF SERVICE	MESSAGE ARRIVAL TIMES	MESSAGE LENGTHS	DESIGNATION
Tactical data interchange link	Periodic	Fixed	D/D
Network control	Random	Fixed	M/D
Teletypewriter	Random	Random	M/M

The total mean message arrival rate, λ, is given by

$$\lambda = \sum_{i=1}^{N} \lambda i \qquad \text{(B-1)}$$

where λ_i is the message arrival rate from the i^{th} message source or terminal and N is the total number of terminals. If all sources generate messages at the same mean rate, λ', we have

$$\lambda = N\lambda'. \qquad \text{(B-2)}$$

The mean message time duration, $\overline{x}$, is the mean message length in bits, $\overline{\ell}$, divided by the transmission bit rate, r, or

$$\overline{x} \equiv \overline{\ell}/r. \qquad \text{(B-3)}$$

The channel utilization factor, ρ, is the fraction of the total channel capacity used to transmit message data and is defined as

$$\rho \equiv \lambda\overline{x} = \lambda\overline{\ell}/r. \qquad \text{(B-4)}$$

Again, if all N sources have the same message generation rate, λ', then equation B-4 becomes

$$\rho = N\lambda'\overline{x} = N\lambda'\overline{\ell}/r. \qquad \text{(B-5)}$$

The fraction of the total channel capacity utilized by a single source to transmit message information, ρ', is defined by

$$\rho' \equiv \lambda'\overline{x} = \lambda'\overline{\ell}/r. \tag{B-6}$$

B.3 ASSIGNMENT SYSTEMS

There are many possible multiple-access, demand assignment control systems. It is convenient to classify systems first in terms of the way in which the channel capacity is assigned among the users and, second, in terms of the method of control (if any) used to assign this division of channel capacity to the users.

For fixed assignment systems, a portion of the total capacity is permanently assigned to each source or terminal. The channel capacity can be divided among the users or terminals by means of frequency or time division multiple access (FDMA or TDMA). For frequency division multiple access (FDMA), the total channel capacity is divided into subchannels of lower capacity so that these subchannels can carry data simultaneously at a lower rate than the total channel capacity. Each subchannel is assigned to a single user. In time division multiple access (TDMA), the channel capacity is divided by allowing the users to access a single high-speed channel sequentially. Each user is given a fixed length time slot so that the frame or cycle is periodic. (In computer systems this form of multiple access is also referred to as synchronous time division multiple access.)

The channel capacity may often be used more efficiently by employing a demand assignment (DA) system. The DA system techniques include polled assignment, reservation assignment, and random assignment systems. In polled assignment, each user is given the channel, in sequence, until the terminal has transmitted all the traffic it has in queue; the cycle will not in general be periodic. (In computer systems this is referred to as asynchronous time division multiple access.) In reservation assignment, a user is assigned the full channel capacity when it has traffic and capacity is available. Reservation systems require an orderwire or control channel for the purpose of requesting and/or granting channel reservations.

In random assignment, the user terminal transmits traffic as it arrives, without any control. Under these conditions there is unresolved contention for the channel, and users will interfere with one another. When interference occurs, the message or packet will be retransmitted after a random delay. When messages are transmitted as fixed length packets, the systems are referred to, in computer systems terminology, as ALOHA type access. If packets are sent with random starting times, the access is known as pure ALOHA. If the packets are restricted to fall in synchronous time slots, the access is known as slotted ALOHA.

The requirements for a control channel vary with the means used to divide and assign the channel capacity. For fixed assignment FDMA, no access control is required. For fixed assignment TDMA, the only control required is a timing channel to mark the beginning for a frame. However, it is often desirable, in either FDMA or TDMA, to provide a control channel to reassign frequency channels or time slots and to increase or decrease the number of time slots in a frame, as in a round-robin system. For polling, control must be provided to sequence the users. This can be done by polling the users in sequence, but it can also be done by each terminal monitoring the channel for the end of transmission of its predecessor.

In a reservation system, an orderwire channel is required to request a channel assignment. The orderwire may be an FDMA channel, a TDMA time slot, or a random assignment channel. Access systems can be compounded. It is reasonable to consider reservation assignment-TDMA-FDMA systems in which the total channel capacity if first divided into frequency channels (FDMA). Each frequency channel is then divided into time slots (TDMA), and each time slot is shared by a network in a reservation assignment system.

The access systems which will be analyzed here are shown in table B-2. In general, rather ideal assumptions will be made so that the performance of the systems given are the best that can be achieved with the generic type.

Table B-2. Access Systems Considered.

SYSTEM NUMBER	ASSIGNMENT TECHNIQUE	DATA CHANNEL MULTIPLE ACCESS TECHNIQUE	CONTROL CHANNEL TECHNIQUE	ALTERNATE NAME
1	Fixed assignment	FDMA	None	
2	Fixed assignment	TDMA	None	Synchronous TDMA
3	Polled assignment	Time sequential	None	Asynchronous TDMA
4	Reservation assignment	Time sequential	TDMA	
5	Reservation assignment	Time sequential	Slotted ALOHA	
6	Random assignment	Time sequential	Pure ALOHA	
7	Random assignment	Time sequential	Slotted ALOHA	

B.4 RESULTS OF SYSTEMS ANALYSIS

The results of analyzing the various store-and-forward systems are presented in this section. The required derivations are presented in paragraph B.5. The results are presented in terms of the equation for the total system waiting time, W. Graphs of the results are also presented. These graphs are, in most cases, a plot of the number of terminals that can be supported for a given mean total system waiting time, W, vs the fraction of the total channel capacity used by a single terminal, ρ'. In order to present the results in a compact form, the mean waiting time, W, is expressed in terms of the normalized mean waiting time, w. This is obtained by dividing W by the mean message duration, or

$$w = W/\overline{x} = W/(\overline{\ell}/r). \tag{B-7}$$

The several types of traffic (presented in paragraph 2) are considered individually here because the results obtained are a function of the traffic type. Those types considered are: 1. fixed length messages with periodic arrivals; 2. fixed length messages with random arrival times; and 3. random length messages with random arrival times.

B.4.1 Fixed Length Messages With Periodic Arrivals

Some systems, such as tactical data interchange links (TADIL), generate periodic fixed length messages. In these systems each of N users generates a single message of ℓ bits every T seconds. Because the traffic is so highly deterministic, only fixed assignment systems using FDMA, TDMA, and TDMA-FDMA systems need to be considered. The traffic is transmitted in synchronous time division multiple access systems as shown in figure B-2. There are two cases to be considered.

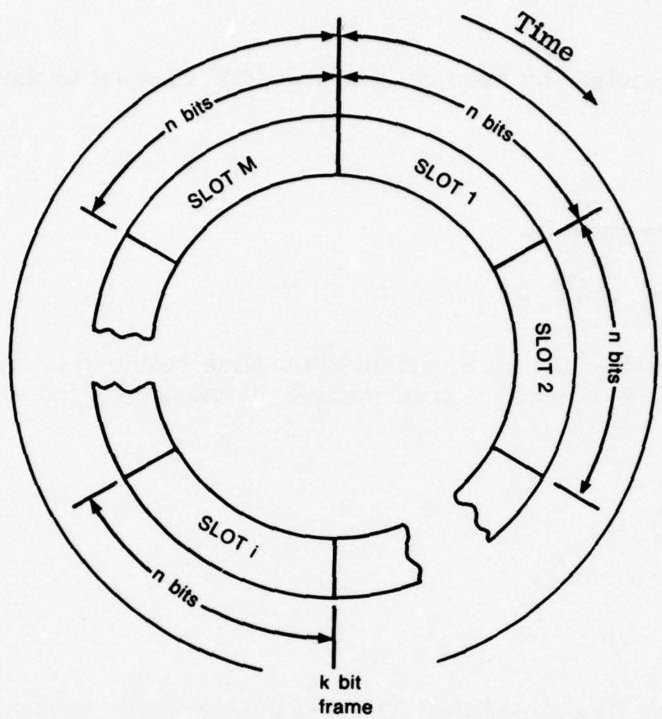


Figure B-2. Synchronous TDMA Frame.

In the first case, the messages are assumed to be generated at the very instant that the time slot becomes available to the user so that there is no delay incurred in waiting for the time slot to become available. This will be referred to as phased arrivals.

In the second case, the messages are generated at a random time in the transmission frame so that the user may have to wait for his time slot before starting transmission. This will be referred to as unphased arrivals.

B.4.1.1 Phased Arrivals

In the first case (phased arrivals), the waiting time using a fixed-assignment TDMA-FDMA system is the exact time required to transmit a message of length ℓ in a TDMA system. The waiting time, W, is given by

$$W = \frac{1}{r}\left[n(m - N) + \ell N\right] \text{ for } 1 \leq m \leq N \;\&\; 1 \leq n \leq \ell \tag{B-8}$$

where r is the total system bit rate, n is the TDMA slot length in bits, m is the number of equal-capacity FDMA channels used, N is the number of users, and ℓ is the number of bits

in a message. It is assumed that ℓ/N and N/m are integers. The bit rate for any one of the FDMA channels, r', is given by

$$r' = r/m. \tag{B-9}$$

The waiting time is minimized by making the slot length, n, equal to the message length, ℓ, or

$$n = \ell. \tag{B-10}$$

The waiting time is then given by

$$W\Big|_{n = \ell} = m\ell/r \quad \text{for } 1 \le m \le N. \tag{B-11}$$

It is convenient to normalize the waiting time to the time required to transmit a message if the full channel capacity is devoted to transmitting the message. Let w be this normalized waiting time so that

$$w \overset{\Delta}{=} W/(\ell/r). \tag{B-12}$$

Using this definition, w becomes

$$w\Big|_{n = \ell} = m. \tag{B-13}$$

This normalized waiting time for phased TDMA-FDMA systems is shown in figure B-3. If a separate FDMA channel is assigned to each user, then m is equal to N, and the normalized waiting time becomes

$$w\Big|_{FDMA} = N. \tag{B-14}$$

From equation B-13 or figure B-3, it is seen that the waiting time is minimized by using a single frequency channel rather than by dividing the users into several FDMA channels. This results from the fact that if all the channel capacity is placed in one channel, the message can be transmitted at a high bit rate and therefore in a shorter time. Note that a "pure" FDMA system is a subset of the above, with $m = N$, and that a "pure" TDMA system is a subset of the above, with $m = 1$.

B.4.1.2 Unphased Arrivals

The second case is that in which the message length is fixed and the arrival time is periodic, but in which the arrivals are phased at random with respect to the frame. In this case there will be a waiting time until the user time slot becomes available. Assuming this portion of the waiting time is a random variable in the ensemble sense, then the mean waiting time is

$$W = \frac{1}{r}\left[n(m - N/2) + \ell N\right] \quad \text{for } 1 \le m \le N \ \& \ 1 \le n \le \ell. \tag{B-15}$$

The number of bits in a slot, n, which minimizes the mean waiting time, w, is again equal to the bits in the message, provided N is greater than 1, so that

$$n = \ell. \tag{B-16}$$

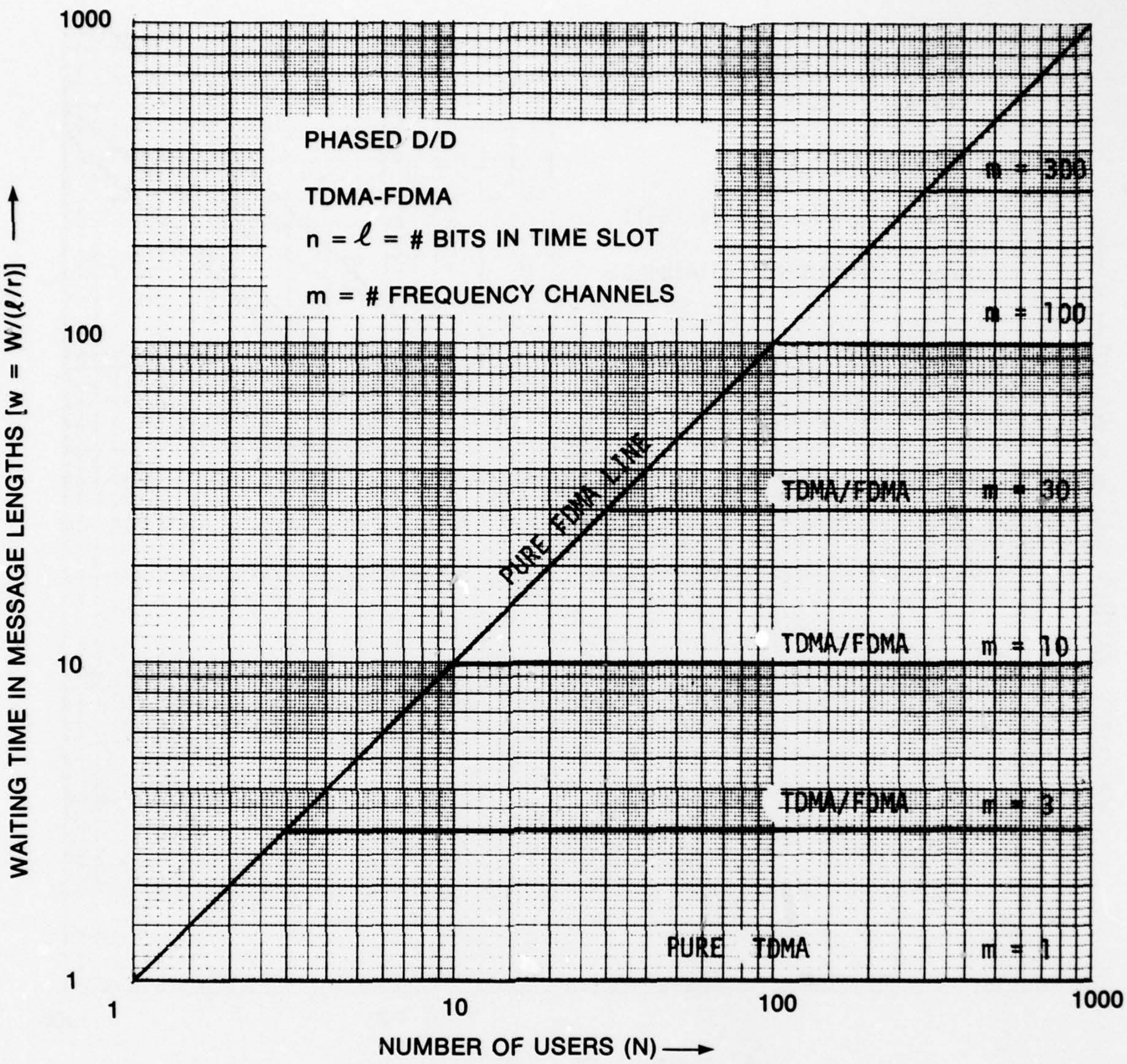


Figure B-3. Waiting Time for Periodic, Fixed Length Messages With Arrivals Phased to Slot Availability Using Fixed Assignment, TDMA-FDMA Access (Equation B-13).

Using this optimum slot length gives

$$W\Big|_{n\,=\,\ell} = \frac{\ell}{r}[m + N/2] \text{ for } 1 \le m \le N \tag{B-17}$$

or

$$w\Big|_{n\,=\,\ell} = m + N/2. \tag{B-18}$$

The normalized mean waiting time for the optimum slot length is plotted in figure B-4.

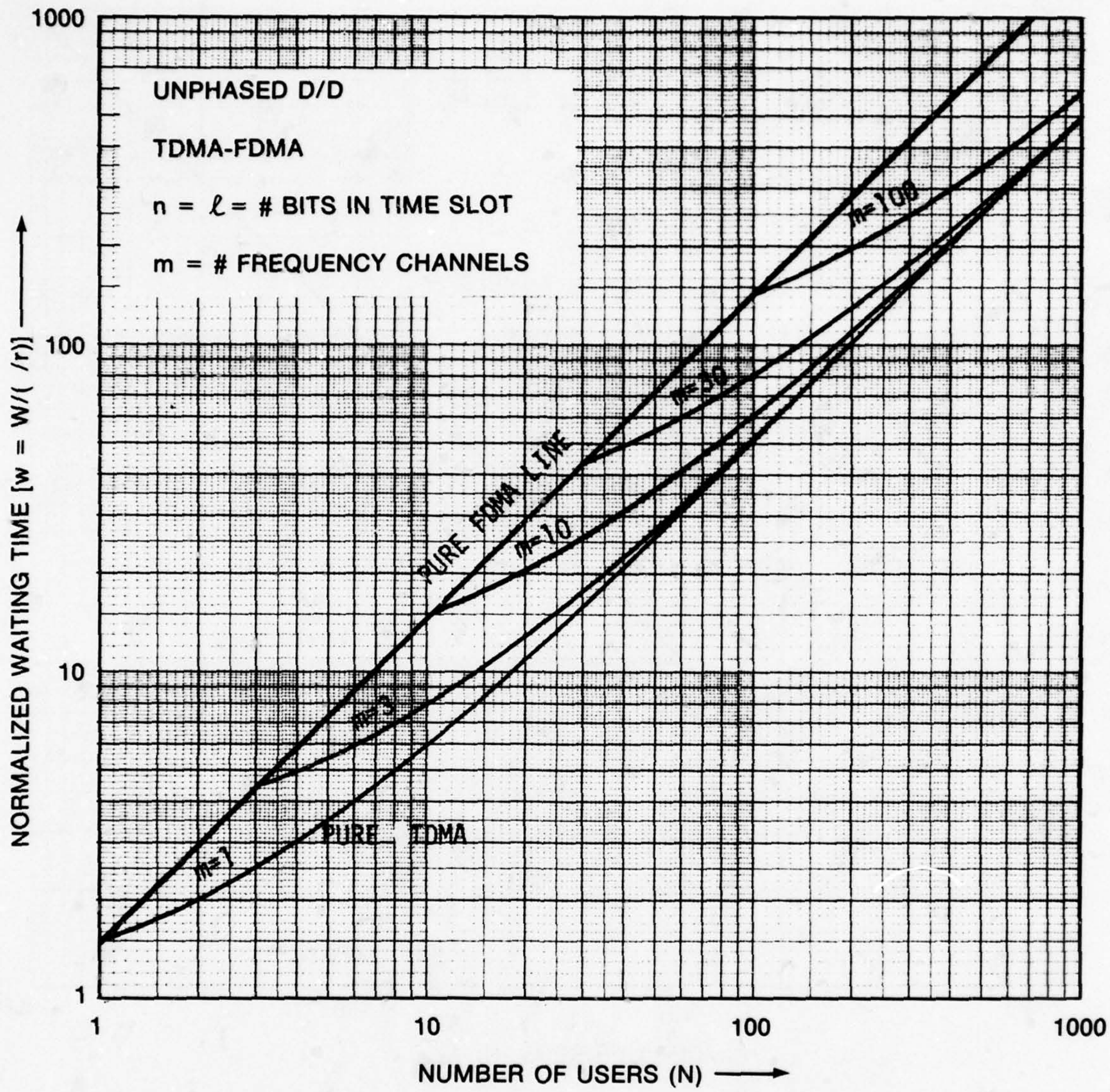


Figure B-4. Waiting Time for Periodic, Fixed Length Messages With Arrivals Unphased to Slot Availability Using Fixed Assignment, TDMA-FDMA Access (Equation B-18).

If a separate FDMA channel is assigned to each user while still maintaining fixed periodic message start times unphased to the message arrivals, then the normalized waiting time becomes

$$w\Big|_{FDMA} = \frac{3}{2} N. \qquad \text{(B-19)}$$

Note the longer waiting time associated with this system as compared to the systems where the message arrivals are phased with the availability of a user's time slot.

Figures B-3 and B-4 can be used to determine the waiting times for systems with fixed length messages and periodic message arrival. It will be noted that in both cases the waiting time is minimized by assigning the full channel capacity to a single TDMA channel rather than by dividing the channel into several, lower bit rate FDMA channels.

B.4.2 Fixed Length Messages With Random Arrival Times

In general, automated orderwire or network control traffic consists of fixed length messages. If the information messages arrive at random, then the arrival times for the control packets will generally also be random. Such traffic can be served either by frequency division multiple access (FDMA), synchronous time division multiple access (TDMA), or random assignment. In general, polling assignment systems are of little interest since, for the most part, no backlog of control messages accumulates at any one terminal. Reservation assignment systems are not generally applicable either, since the primary function of most control traffic is to provide for message traffic, and it makes little sense to provide reservations for the control packets since these packets are very short. Therefore, we shall consider only FDMA, TDMA, and random assignment. The fixed message length of ℓ bits includes all preamble bits plus the bit spaces allowed for guard times.

B.4.2.1 FDMA

One method of providing the network control function is to provide a separate low-bit-rate FDMA control channel to each user. The bit rate, r', for a single FDMA channel is

$$r' = r/N, \tag{B-20}$$

where r is the combined bit rate for all channels and N is the number of users and the number of FDMA channels. The mean waiting time, W, in a system of this type is given by

$$W = \frac{\ell}{r} \frac{N}{2} \left(\frac{2 - N\rho'}{1 - N\rho'}\right), \tag{B-21}$$

where ℓ is the message length, and ρ' is the fraction of the total channel capacity used by a single terminal.

The waiting time is a function of the number of users, N, sharing the channel, and the average portion of the total communications capacity each user is demanding (ρ'). This general situation arises repeatedly. A convenient way of presenting these analytical results is to plot a curve of constant waiting time in the N vs ρ' plane as shown in figure B-5. It is further useful to plot these curves with normalized waiting time $w = W/(\ell/r)$ as the parameter. The normalized waiting time is the mean waiting time measured in terms of the time required to transmit the average message using the total bit rate capacity of the system.

The maximum allowable normalized waiting time, w_{max}, is given by

$$w_{max} = W_{max}/(\ell/r). \tag{B-22}$$

The portion of the N vs ρ' plane, which is below the appropriate w_{max} curve on this plot, represents all traffic levels which meet the waiting time requirement using the particular assignment system. Since the system utilization factor, ρ, is defined as

$$\rho = N\rho' , \tag{B-23}$$

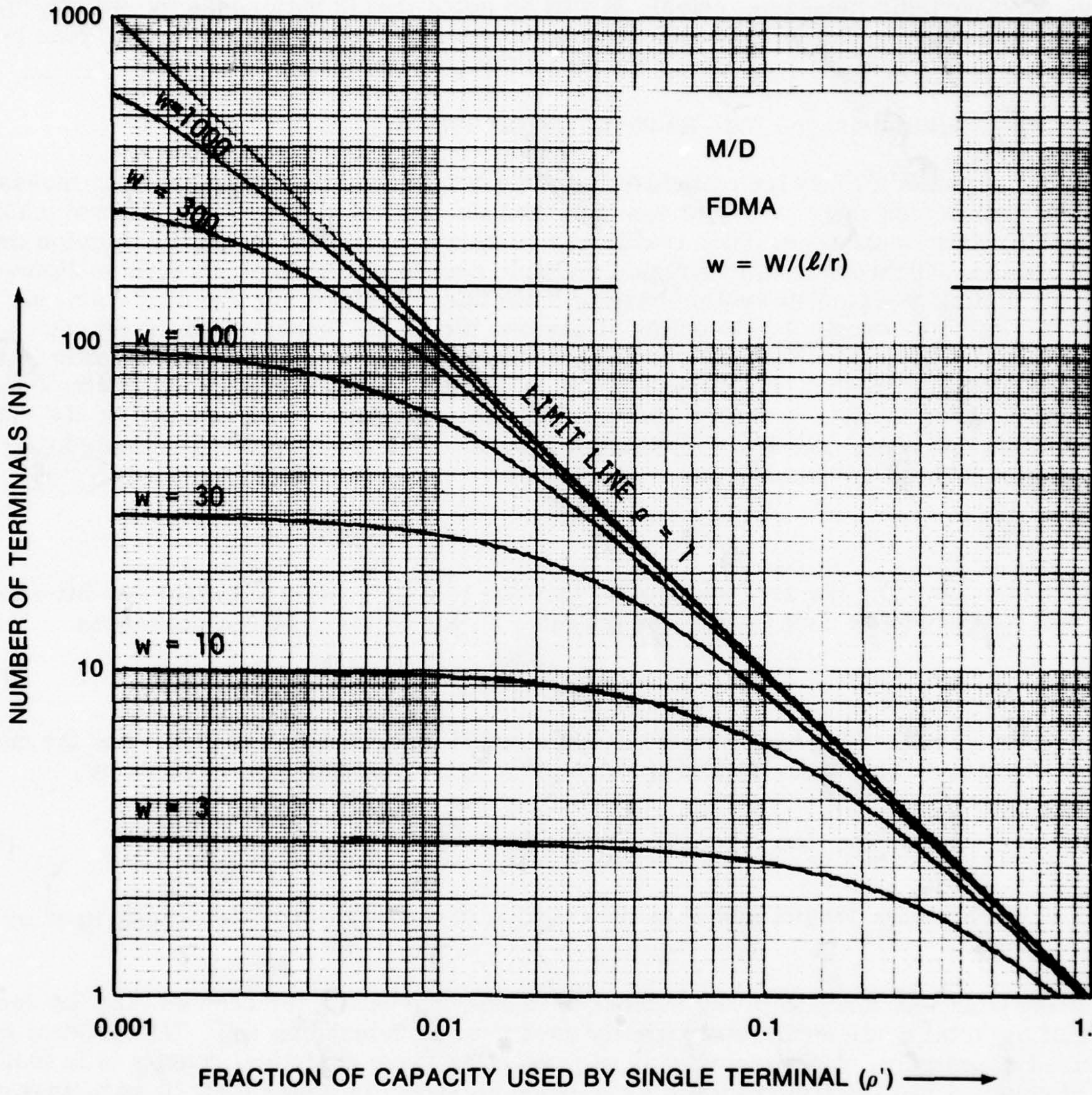


Figure B-5. Fixed Assignment FDMA System Waiting Time (w) for Fixed Length Messages With Random Arrivals (Equation B-21). w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

it follows that constant utilization factor lines are straight lines with a -45° slope on log-log paper. Thus, the utilization factor at each point in the N vs ρ' plane is readily determined. The ρ = 1 line shown on the N vs ρ' plot is the upper bound of performance for all systems.

B.4.2.2 TDMA

Another method of providing the network control function is to provide synchronous time division multiple access. The mean waiting time for TDMA channels, W, is given by

$$W = \frac{\ell}{r}\left(\frac{N}{2}\left[\frac{1}{1 - N\rho'}\right] + 1\right), \tag{B-24}$$

where ℓ is the fixed message length, N is the number of users, ρ' is the utilization factor for a single user, and r is bit rate. The optimum slot length for $N > 1$ is equal to the message length, ℓ, and this slot length is assumed in equation B-24. This result is plotted in figure B-6 in the N vs ρ' plane.

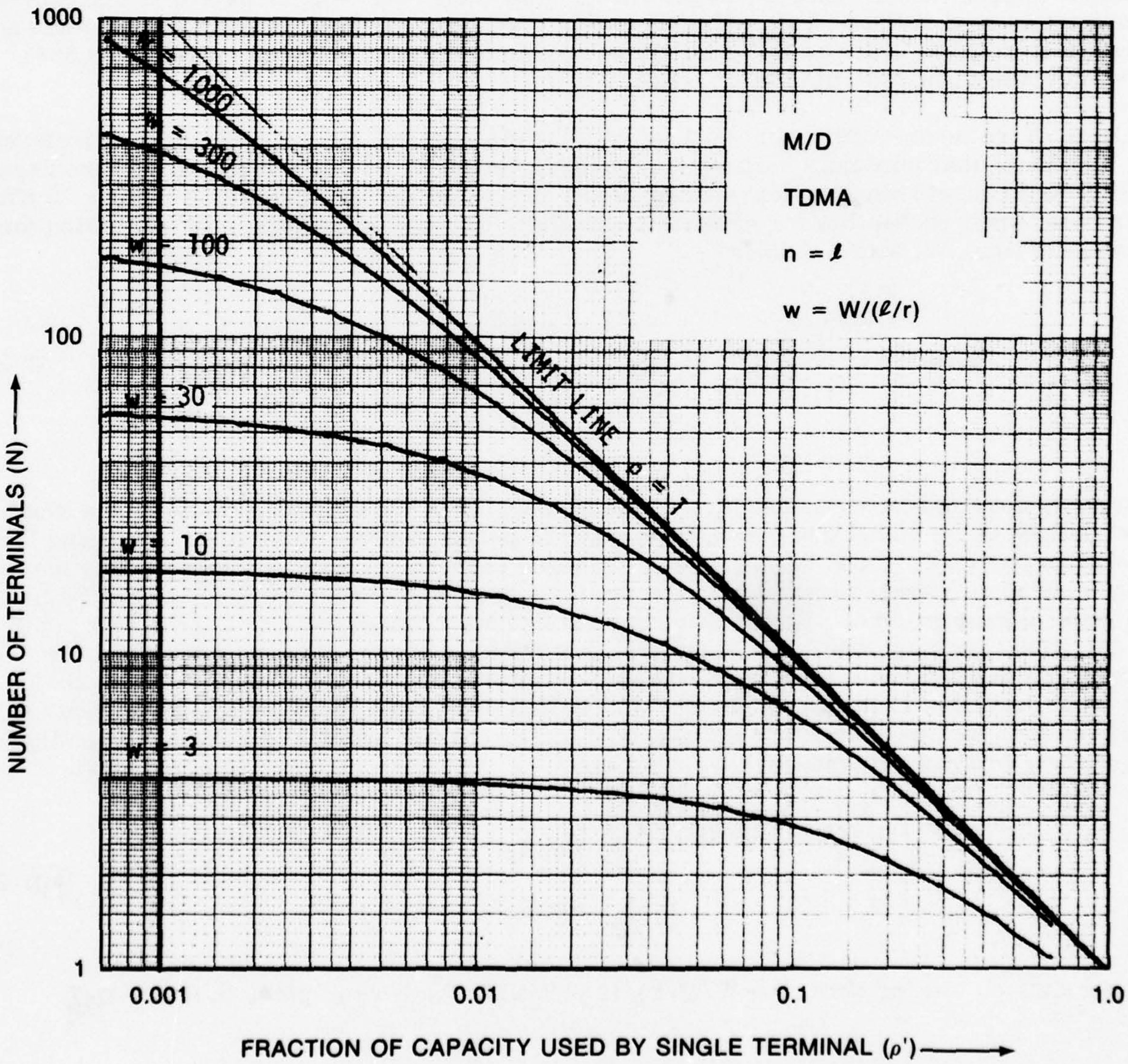


Figure B-6. Fixed Assignment TDMA System Waiting Time (w) for Fixed Length Messages With Random Arrivals (Equation B-24). w = Normalized System Waiting Time in Message Lengths = $W/(\ell/r)$; n = Slot Length in Bits.

B.4.2.3 Random Assignment

The network control function can also be performed by a random access system. There are two basic types of random access systems for fixed length messages. The first is an asynchronous random access system in which a message is transmitted as soon as it appears at the terminal. If two or more users' transmissions overlap, as determined by monitoring or acknowledgement, then all messages are destroyed and must be retransmitted. If a message is destroyed, it is retransmitted after a random delay. This system is known as pure ALOHA. It has been shown (reference 2) that the maximum channel utilization factor, ρ, for pure ALOHA systems is 1/2e or 0.184. If the average of new traffic arrivals exceeds this, the system saturates and the data throughput decreases to zero. Because of the relatively low maximum utilization factor, pure ALOHA will not be considered further.

The second system is synchronous random access, known as slotted ALOHA. This system is identical to pure ALOHA except that the fixed length packet transmissions are synchronized in time slots so that the packets will arrive in a fixed time window. In this system, messages either overlap completely or not at all. The maximum utilization factor, ρ, is 1/e (0.368), which is twice as high as for pure ALOHA.

Analysis of the mean waiting time in a slotted ALOHA system is given by Kleinrock (reference 2). It is found that minimum waiting time is achieved under all reasonable channel loadings if destroyed packet transmissions are randomly rescheduled into one of the following 15 time slots, with equal probability for each time slot (K = 15). A simple approximate equation for the waiting time, W, with K = 15 is

$$W = \begin{cases} \frac{\ell}{r}\left\{D_p + 1 + 4\left[D_p + 8\right](N\rho')^{3/2}\right\} & \text{for } N\rho' < 0.35 \\ \infty & \text{for } N\rho' \geq 0.35 \end{cases} \tag{B-25}$$

where ℓ is the fixed message length, r is the bit rate, ρ' is the utilization factor for a single user, and D_p is the round trip propagation delay in packet lengths required to determine that a message has experienced interference, measured in message lengths. The propagation delay adds an additional parameter to the problem, making it difficult to present the results in a general graphic form. By time sharing a frequency channel between the network control and the actual message traffic, it is generally possible to arrange the system so that the propagation delay will not directly increase the waiting time. Thus, it is possible to avoid additional delay due to propagation since during this delay time the channel can be used for other traffic. We shall therefore set D_p equal to zero in our present treatment. When the propagation delay is set equal to zero, we have

$$W = \begin{cases} \frac{\ell}{r}\left\{1 + 32(N\rho')^{3/2}\right\} & \text{for } N\rho' < 0.35 \\ \infty & \text{for } N\rho' \geq 0.35 \end{cases} \tag{B-26}$$

The normalized waiting time, $w = W/(\ell/r)$, is plotted in the N vs ρ' plane in figure B-7.

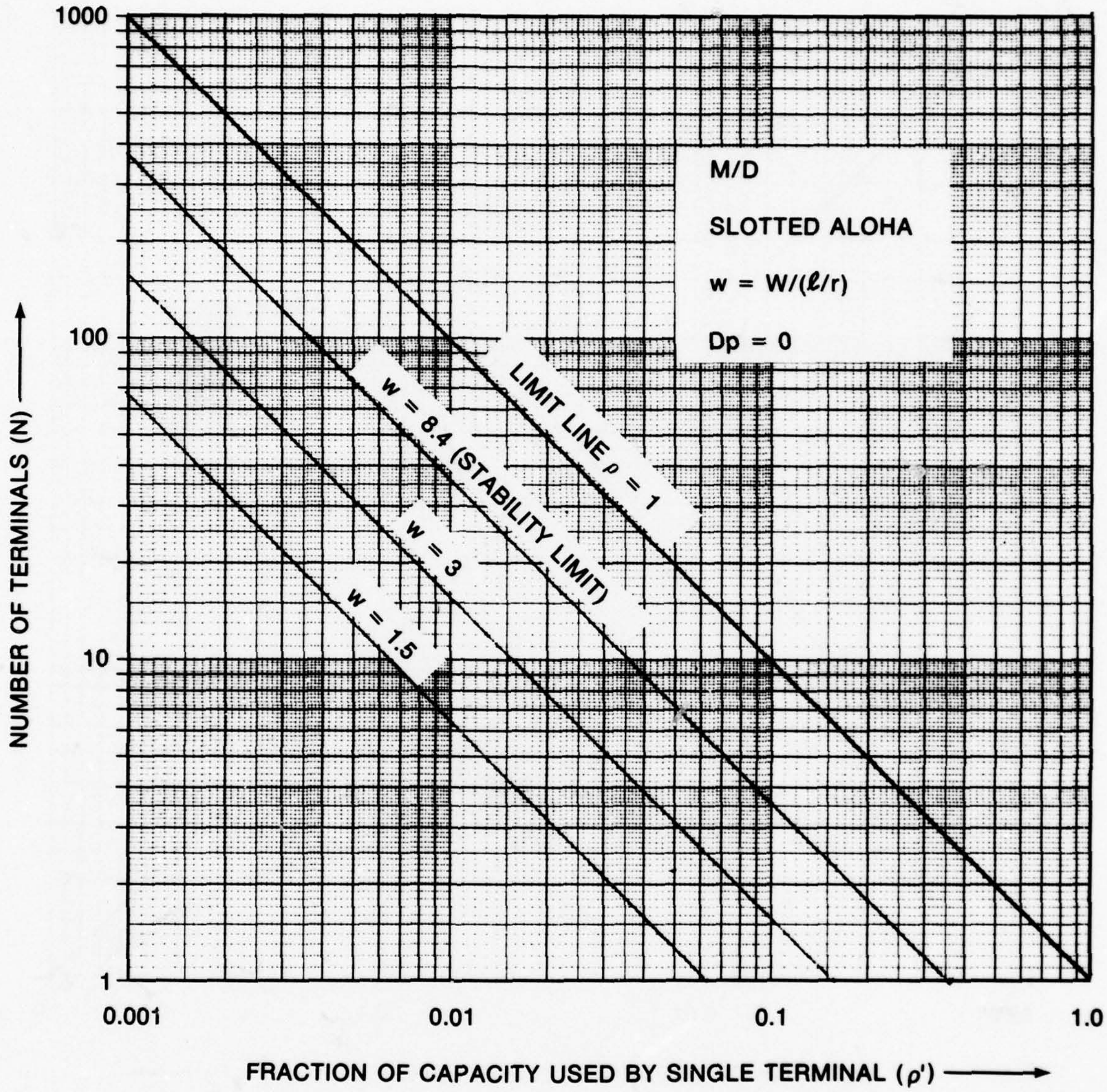


Figure B-7. Slotted ALOHA System Waiting Time (w) for Fixed Length Messages With Random Arrivals (Equation B-26). w = Normalized System Waiting Time in Message Lengths = $W/(\ell/r)$.

B.4.2.4 Comparison of Systems for Fixed Length Messages With Random Arrivals

Comparing the performance of FDMA with TDMA, as shown in figures B-5 and B-6, shows that the TDMA system results in a shorter waiting time in all cases where the number of terminals exceeds 2. TDMA, therefore, is generally preferred. In comparing TDMA and slotted ALOHA (figures B-6 and B-7), however, it is seen that TDMA gives the shortest waiting time for a low number of users with a large amount of traffic, while slotted ALOHA gives the shortest waiting time for a large number of low-duty-cycle users. Composite plots comparing the systems are shown in figures B-8 through B-10.

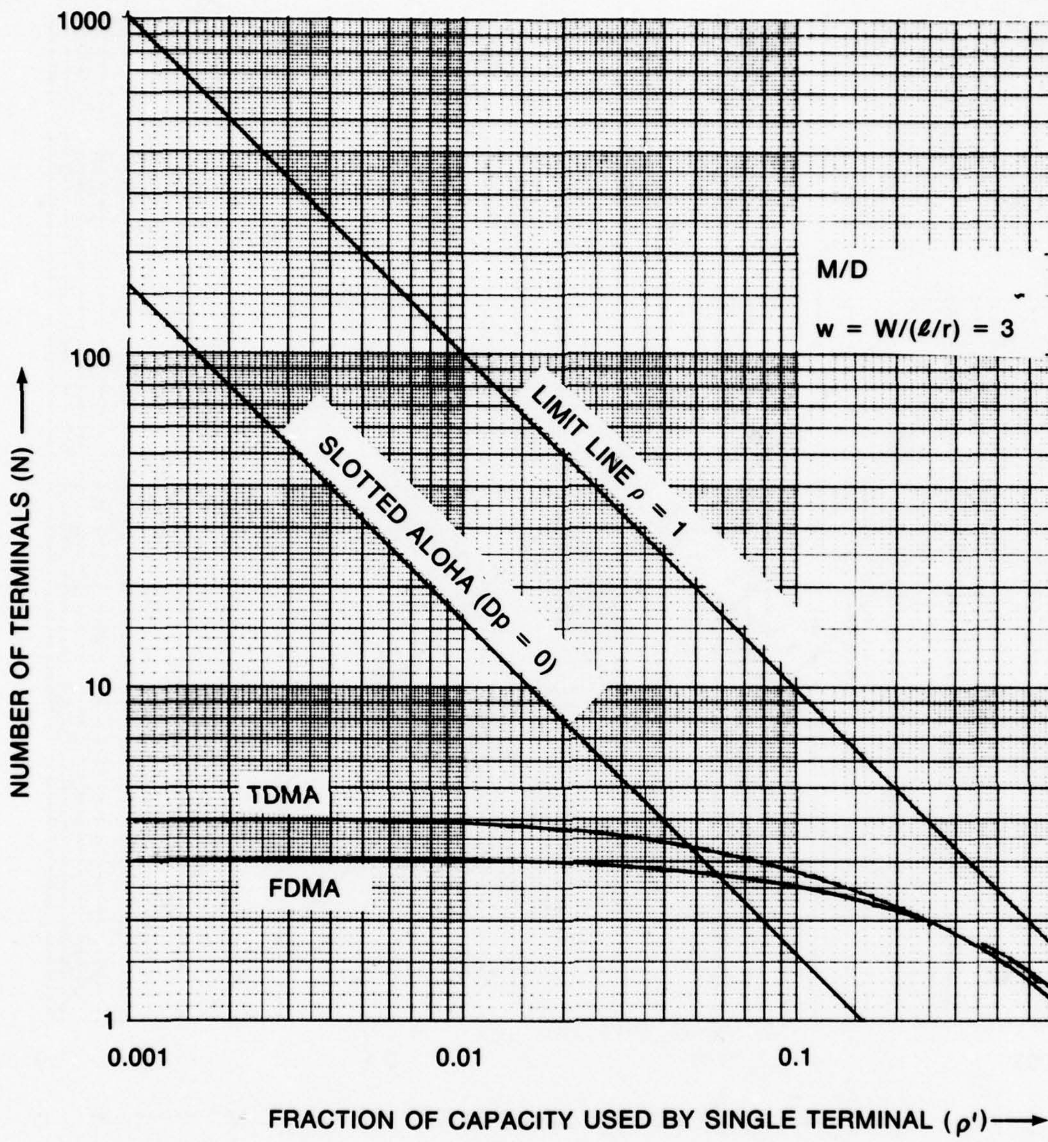


Figure B-8. Comparison of Systems for w = 3 for Fixed Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

In figure B-11, the areas in the N vs ρ' plane for which each system is optimum is shown to further aid comparison. Since the traffic models may change with time or may not be known accurately, it is not always desirable to choose the system which gives the minimum waiting time. It is often more desirable to pick a system which provides an acceptable maximum waiting time over the largest portion of the N vs ρ' plane in the general area of interest.

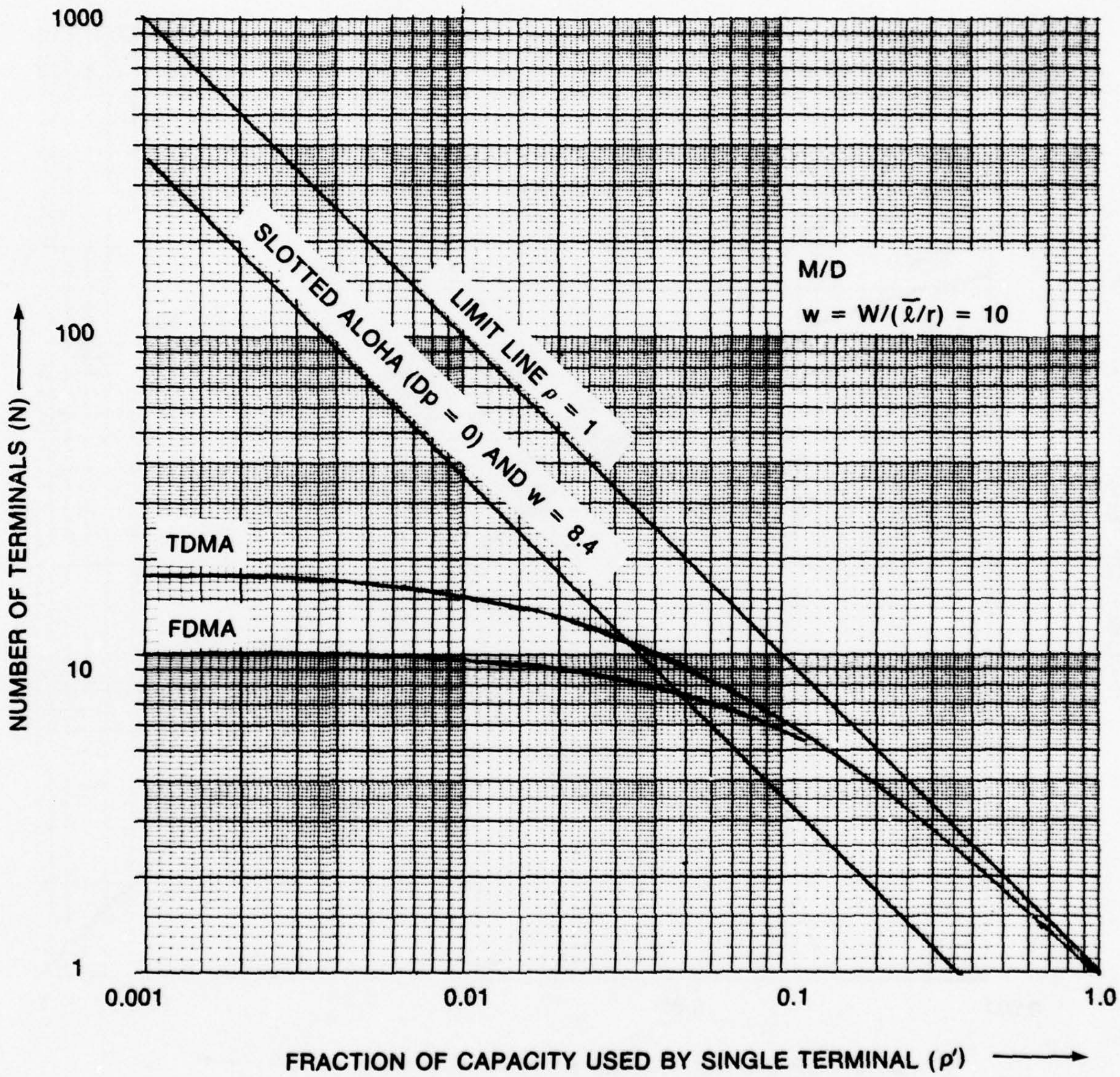


Figure B-9. Comparison of Systems for $w = 10$ for Fixed Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

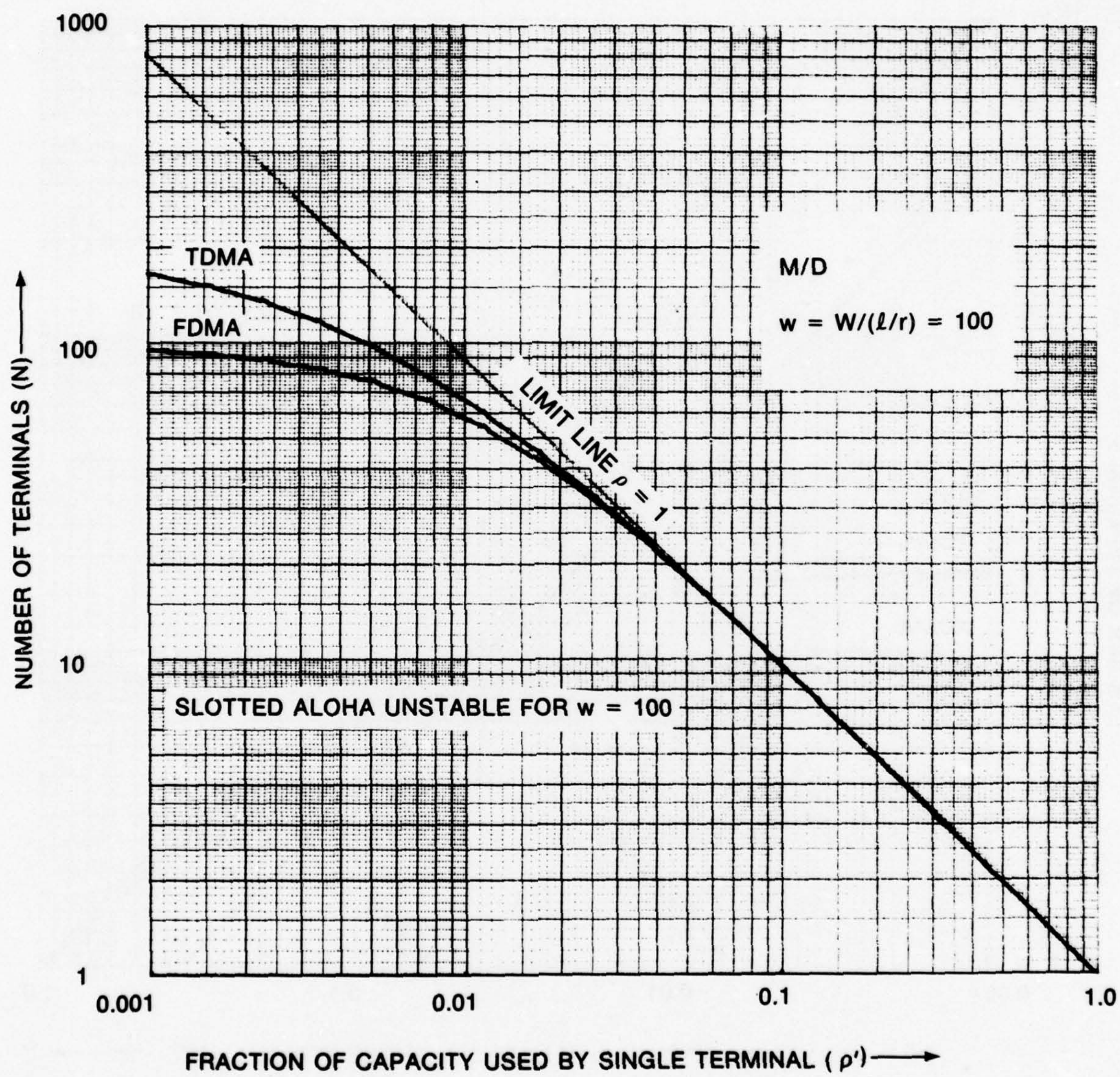


Figure B-10. Comparison of Systems for w = 100 for Fixed Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\ell/r)$.

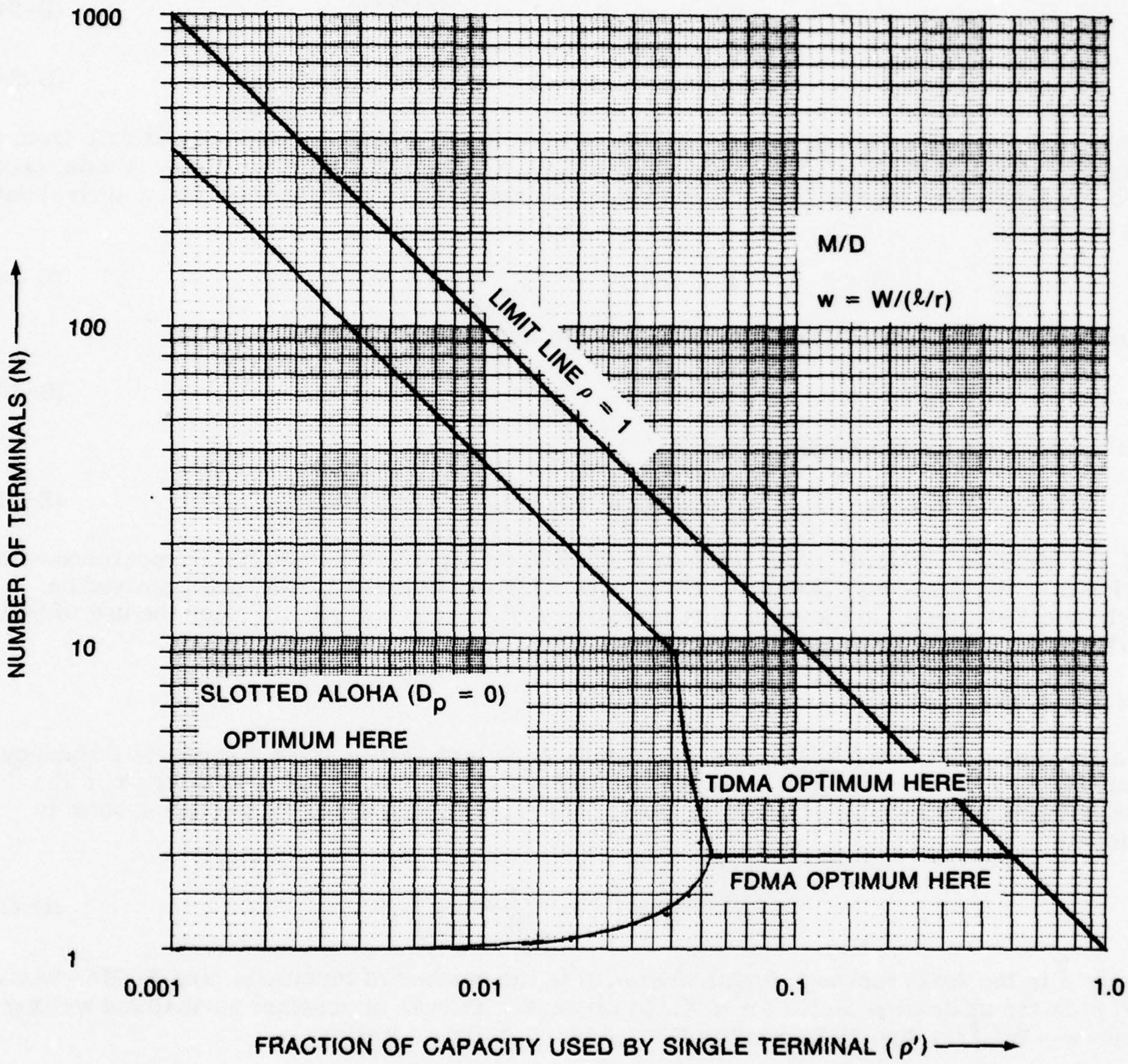


Figure B-11. Areas of Which Each Type Access System Gives Minimum Waiting Time for Fixed Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

B.4.3 Random Length Messages With Random Arrival Times

For teletypewriter traffic, the message lengths and message arrival times are both random variables. We will assume that both the message length, ℓ, and the message interarrival time for a single source, $\Delta t'$, are exponentially distributed with the probability functions:

$$P(\ell/r < x) = 1 - e^{-x/(\bar{\ell}/r)}, \tag{B-27}$$

$$P(\Delta t' < t) = 1 - e^{-\lambda' t}. \tag{B-28}$$

Again, $\bar{\ell}$ is the mean message length in bits and λ' is the mean message arrival rate from a single terminal in messages per second. It will be assumed that there are N terminals, each with the same mean message length and mean arrival rate, so that the total mean arrival rate, λ, is

$$\lambda = n\lambda'. \tag{B-29}$$

The amount of the total capacity used by a single terminal, ρ', is given by

$$\rho' = \lambda'\bar{\ell}/r, \tag{B-30}$$

and the total utilization factor, ρ, is

$$\rho = N\rho' = N\lambda'\bar{\ell}/r. \tag{B-31}$$

We will consider systems using frequency division multiple access (FDMA), synchronous time division multiple access (TDMA), polling, pure ALOHA, slotted ALOHA, and reservation assignment systems. In the case of reservation assignment, we will consider the use of both TDMA and slotted ALOHA on the orderwire.

B.4.3.1 FDMA

In a frequency division multiple access system, each terminal is given a separate frequency channel. The bit rate that can be supported on each FDMA channel is r/N, where r is the total bit rate which the system can support. The total waiting time, W, for this system is given by

$$\overline{W} = \frac{\bar{\ell}}{r}N\left(\frac{1}{1 - (N \cdot \rho')}\right), \tag{B-32}$$

where $\bar{\ell}$ is the mean message length in bits, N is the number of terminals (and FDMA channels), and ρ' is the utilization factor for a single terminal. Curves of constant normalized waiting time, $w = W/(\bar{\ell}/r)$, are plotted in the N vs ρ' plane in figure B-12.

B.4.3.2 TDMA

In synchronous time division multiple access, each terminal is assigned a time slot in which to transmit its messages. Each terminal stores all arriving messages in a local buffer and empties this buffer as time allows when its time slot occurs. The time slot lengths are fixed at "b" information bits plus "a" bits allowed for guard time and preamble. With this

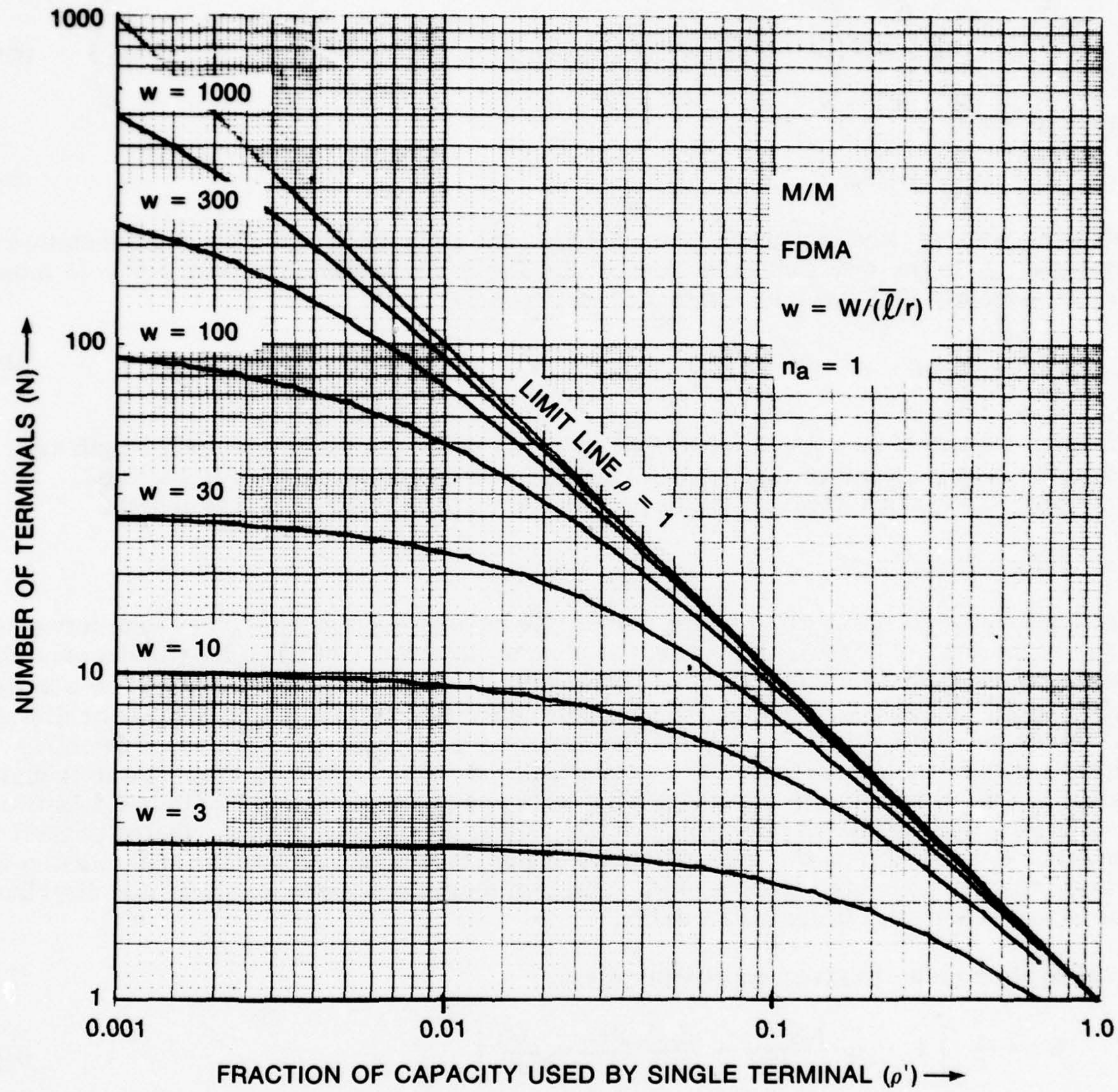


Figure B-12. FDMA System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-32). w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

arrangement all messages, as transmitted, are assumed to be integral multiples of b information bits, and the mean message length, $\overline{m}$, measured in b's becomes

$$\overline{m} = 1/(1 - e^{-b/\bar{\ell}}). \tag{B-33}$$

The total system waiting time is

$$W = \frac{\overline{\ell}}{r}\frac{\alpha}{2}\left\{\overline{m}N\left\{\frac{2 - \alpha\overline{m}N\rho'\left[1 - (1 - 1/\overline{m})(b/\overline{\ell}/\alpha)^2\right]}{1 - \alpha\overline{m}N\rho'}\right\} - (N - 2)\right\} \tag{B-34}$$

where α is given by

$$\alpha = (a + b)/\overline{\ell}. \tag{B-35}$$

In TDMA the waiting time depends on the choice of the ratio of the number of information bits per time slot, b, to the mean message length, $\overline{\ell}$. The $b/\overline{\ell}$ ratio which minimizes w is found to be approximately that given by Wolman (reference 4), or

$$b/\overline{\ell}\Big|_{\text{optimum}} \simeq \sqrt{2a/\overline{\ell}}\,. \tag{B-36}$$

The constant waiting time curves for TDMA systems using the optimum block length are plotted in the N vs ρ' plane in figures B-13 and B-14 for $a/\overline{\ell}$ values of 0.01 and 0.03, respectively, which are typical ratios of preamble length to mean message length.

B.4.3.3 Polled Assignment

In a polling or asynchronous time division multiple access system, the users take turns at using the channel as in TDMA. However, the time slots are not of fixed length and once the channel is turned over to a user, that user has exclusive use of the channel until he empties his buffer of all messages. The control of a polling system can be either central or distributed. In central control, the control station monitors the traffic and, when one terminal completes its transmission, the control station polls the next station in sequence to transmit its traffic. In this system, the minimum delay between user message transmission is two round-trip propagation delays plus time for the polling message. In a distributed control system, each user monitors the transmissions of the other user and starts transmission when the preceding user ends his transmission. The minimum delay between users for distributed control is one round-trip propagation delay.

The total system delay is given approximately by

$$W = \frac{\overline{\ell}}{r}\left[1 + \frac{N\rho'}{1 - N\rho'} + \frac{d/\overline{\ell}}{2}\,\frac{N(1 - \rho')}{1 - N\rho'}\right] \tag{B-37}$$

where $\overline{\ell}$ is the mean message length in bits, r is the channel bit rate, d is the total delay between user message transmissions (preamble, polling, and propagation) in bits, N is the number of terminals, and ρ' is the utilization factor of a single terminal $(\lambda'\overline{\ell}/r)$. N vs ρ' plots for polling systems with $d/\overline{\ell}$ values of from 0.01 to 0.3 are shown in figures B-15 through B-18. For all values of $d/\overline{\ell}$ considered, the polling systems perform better than either FDMA or TDMA systems.

B.4.3.4 Random Assignment

There are two types of random assignment which might be considered for transmission of messages with random arrivals and random lengths.

The first system is pure ALOHA, in which the messages are broken into blocks of fixed length and transmitted as ALOHA for fixed length messages as described in paragraph B.4.2.3. Here the maximum utilization factor obtainable is less than 0.19. The utilization factor is so low that this system will not be considered further.

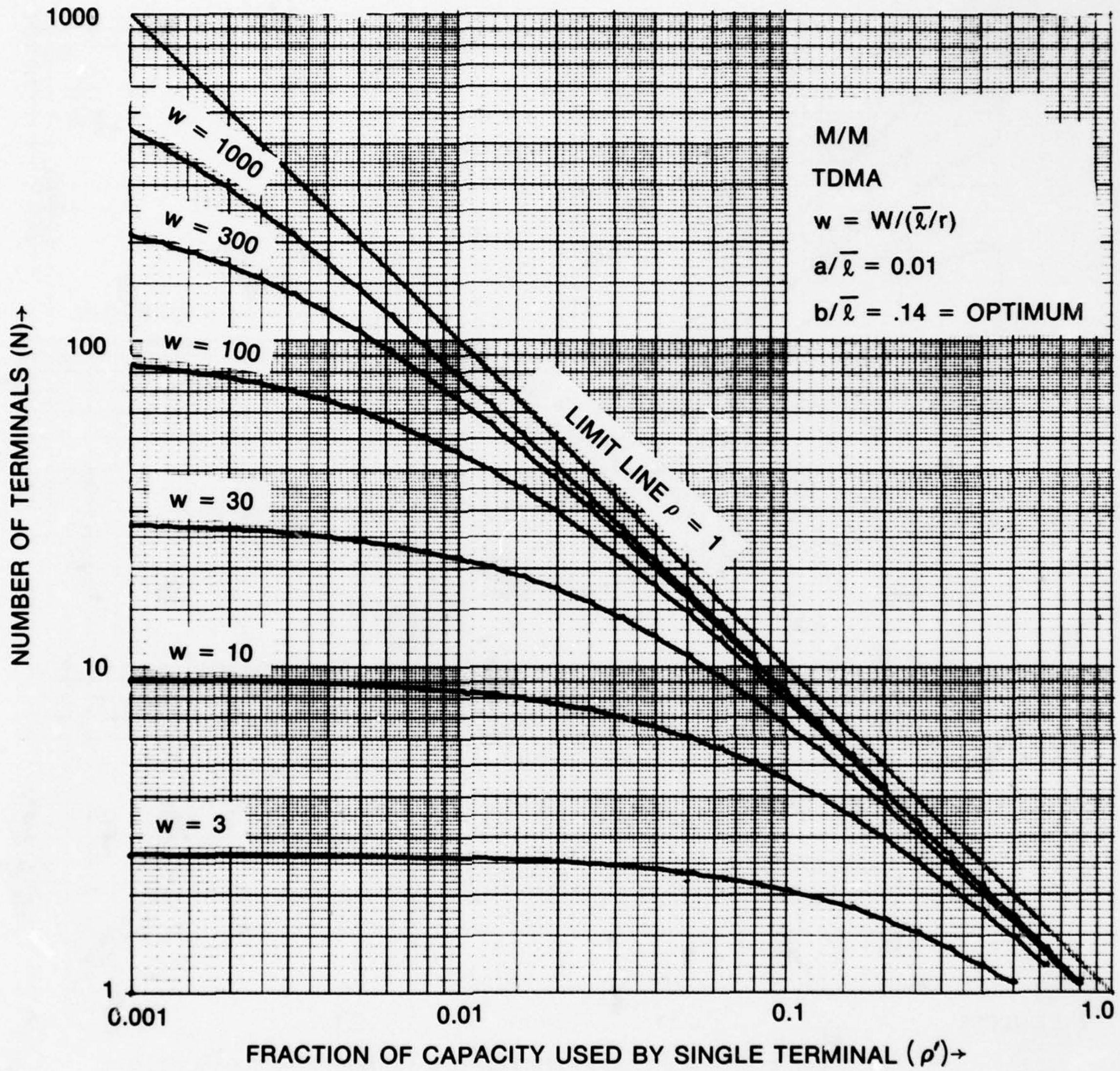


Figure B-13. TDMA System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-34) for $a/\bar{\ell} = 0.01$. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

The second system is slotted ALOHA in which the message is broken into blocks of fixed length; these blocks are transmitted in fixed time slots but without any control. If the block is interfered with, as determined by self-monitoring of the channel, the block is repeated. This is essentially the system described in paragraph B.4.2.3. To a rough approximation, the results of this previous paragraph can be used if the message generation rate, λ', is modified to account for the increase in the number of blocks which must be transmitted to transmit a single message. While this approximation is quite crude, it places a lower bound

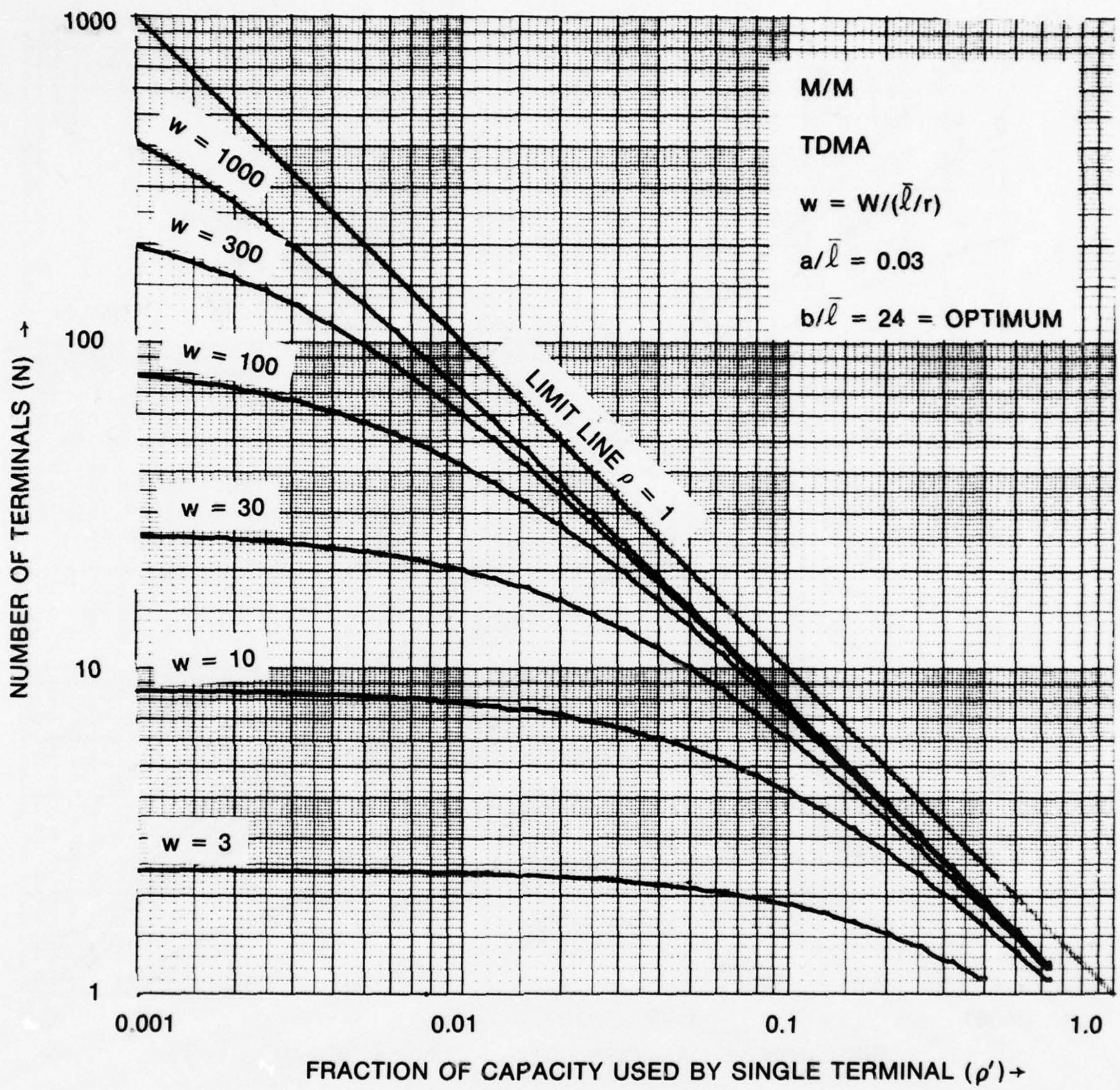


Figure B-14. TDMA System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-34) for $a/\bar{\ell} = 0.03$. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

on the system waiting time. As it turns out, even this lower bound does not make the system attractive for the range of traffic models and allowable waiting times considered in this report.

The mean number of blocks, $\overline{m}$, required to transmit a message with a mean length of $\bar{\ell}$ bits is

$$\overline{m} = \frac{1}{(1 - e^{-b/\bar{\ell}})} , \qquad \text{(B-38)}$$

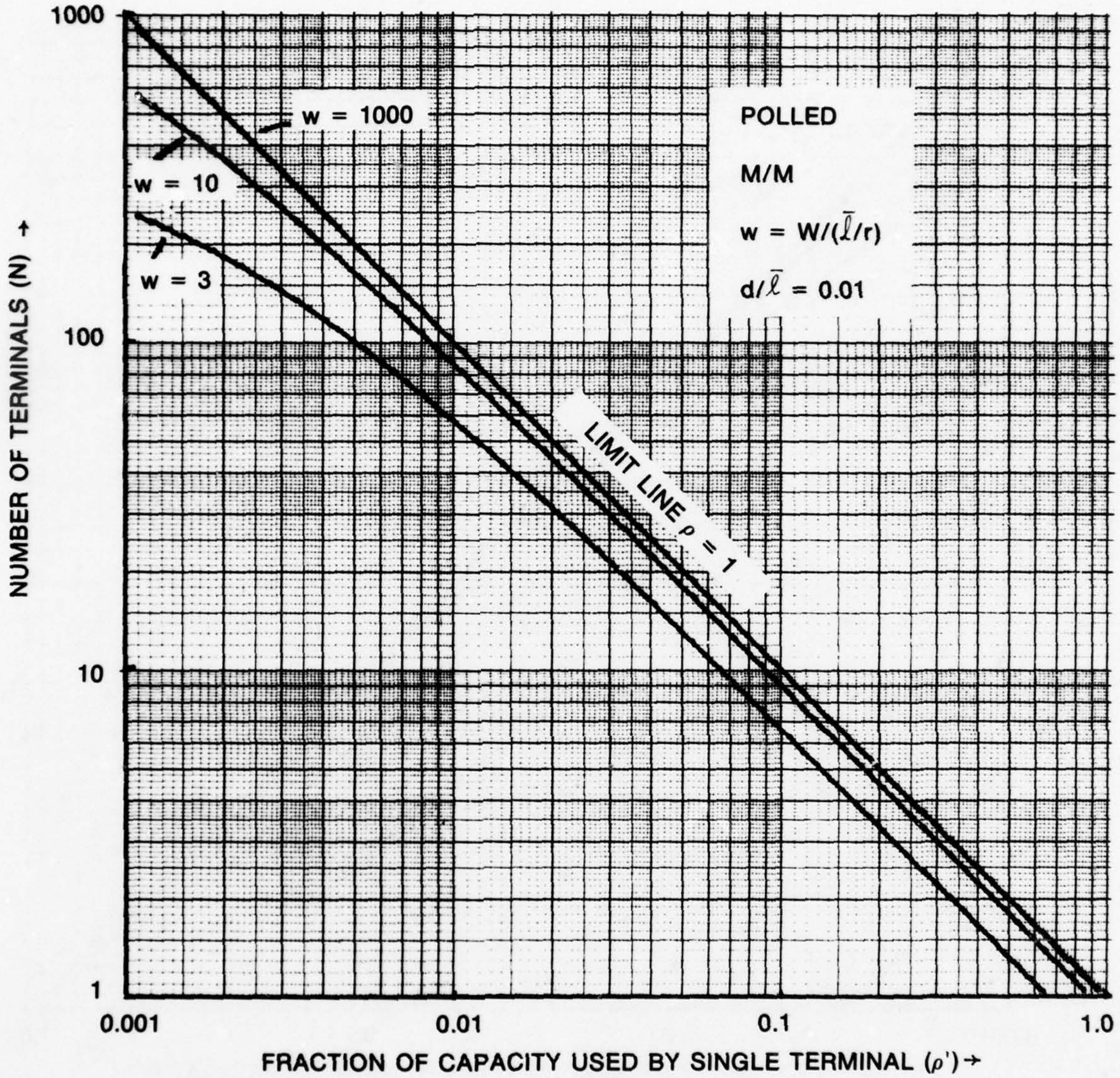


Figure B-15. Polled System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-37) for $d/\bar{\ell} = 0.01$. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell} r)$.

where b is the number of information bits in a block. The block requires a preamble and guard time of "a" bits so that the total block length is a + b bits long. The optimum number of information bits in a block is approximately (reference 4)

$$b/\bar{\ell} = \sqrt{2a/\bar{\ell}}. \qquad \text{(B-39)}$$

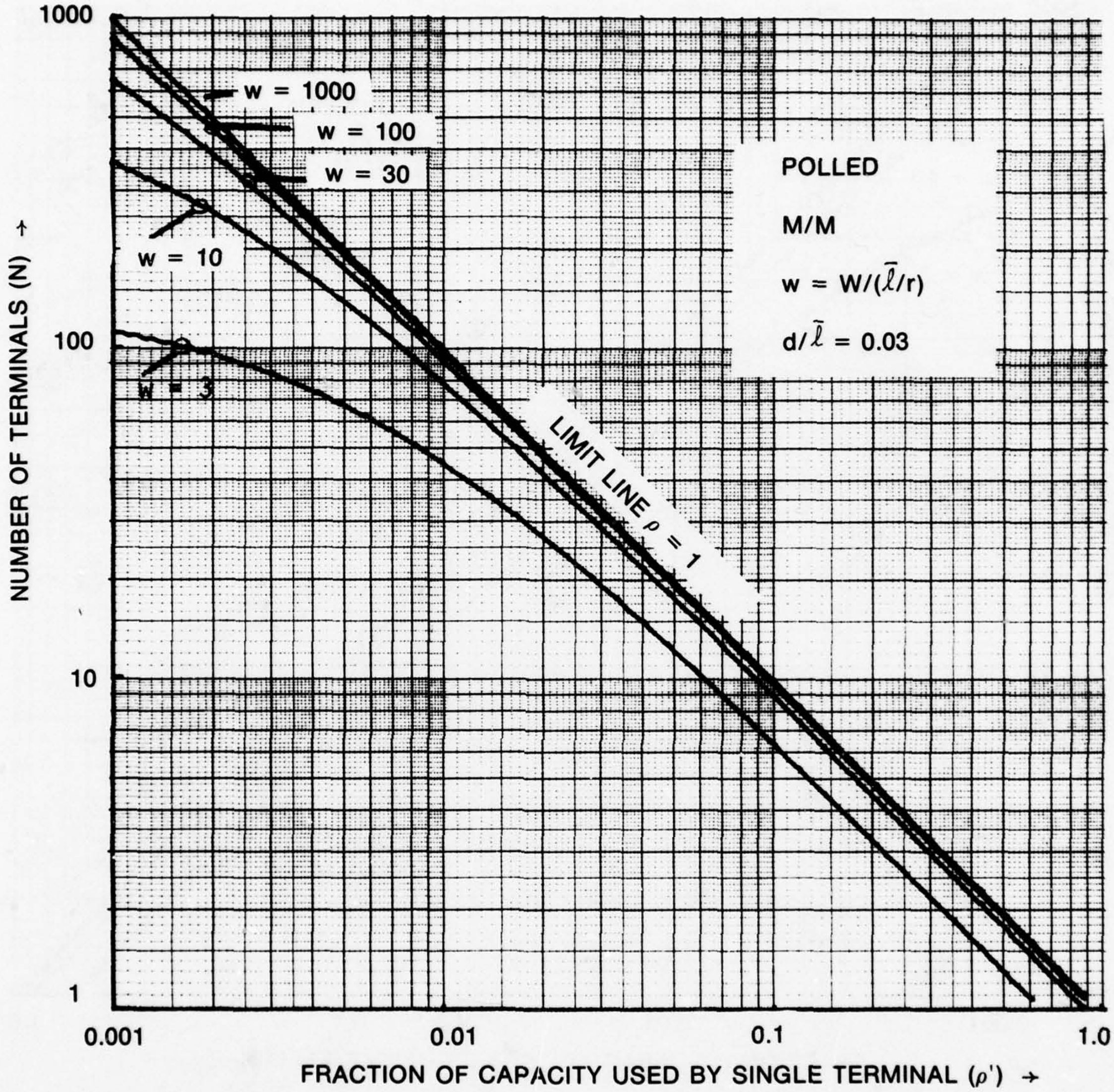


Figure B-16. Polled System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-37) for $d/\bar{\ell} = 0.03$. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

Using these results in equation B-26 gives the mean waiting time for one block, W_1, as

$$W_1 = \frac{\bar{\ell}}{r}(a/\bar{\ell} + b/\bar{\ell})\left\{1 + 32[\bar{m}(a/\bar{\ell} + b/\bar{\ell})]^{3/2}[N\rho']^{3/2}\right\} \qquad \text{(B-40)}$$

which is valid for

$$\bar{m}(a/\bar{\ell} + b/\bar{\ell})N\rho' < 0.35.$$

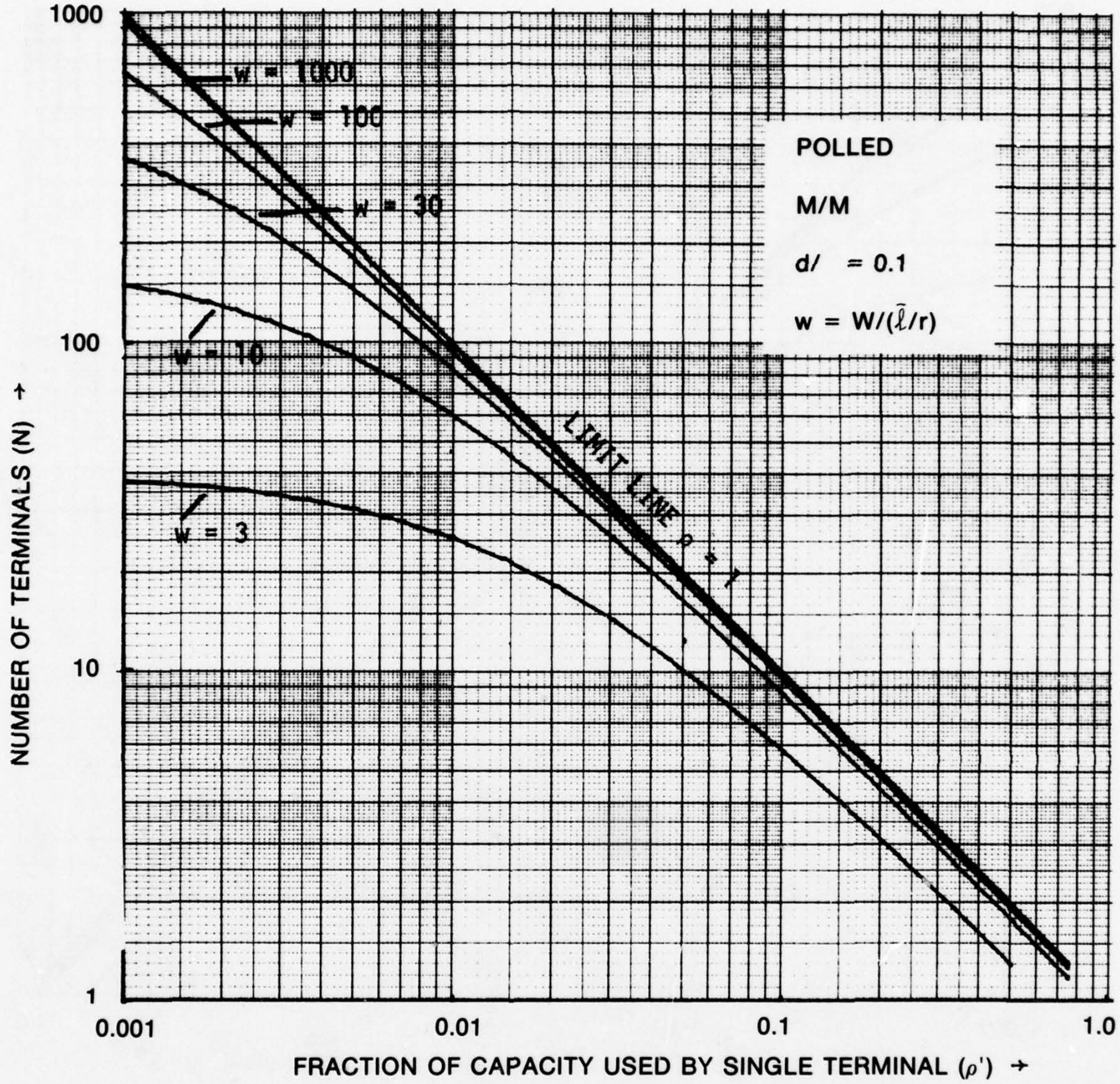


Figure B-17. Polled System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-37) for $d/\ell = 0.1$.
w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

The total mean system waiting time is

$$W = \overline{m}W_1$$

$$= \frac{\bar{\ell}}{r}\,\overline{m}(a/\bar{\ell} + b/\bar{\ell})\left\{1 + 32\left[\overline{m}(a/\bar{\ell} + b/\bar{\ell})\right]^{3/2}\left[N\rho'\right]^{3/2}\right\} \quad \text{(B-41)}$$

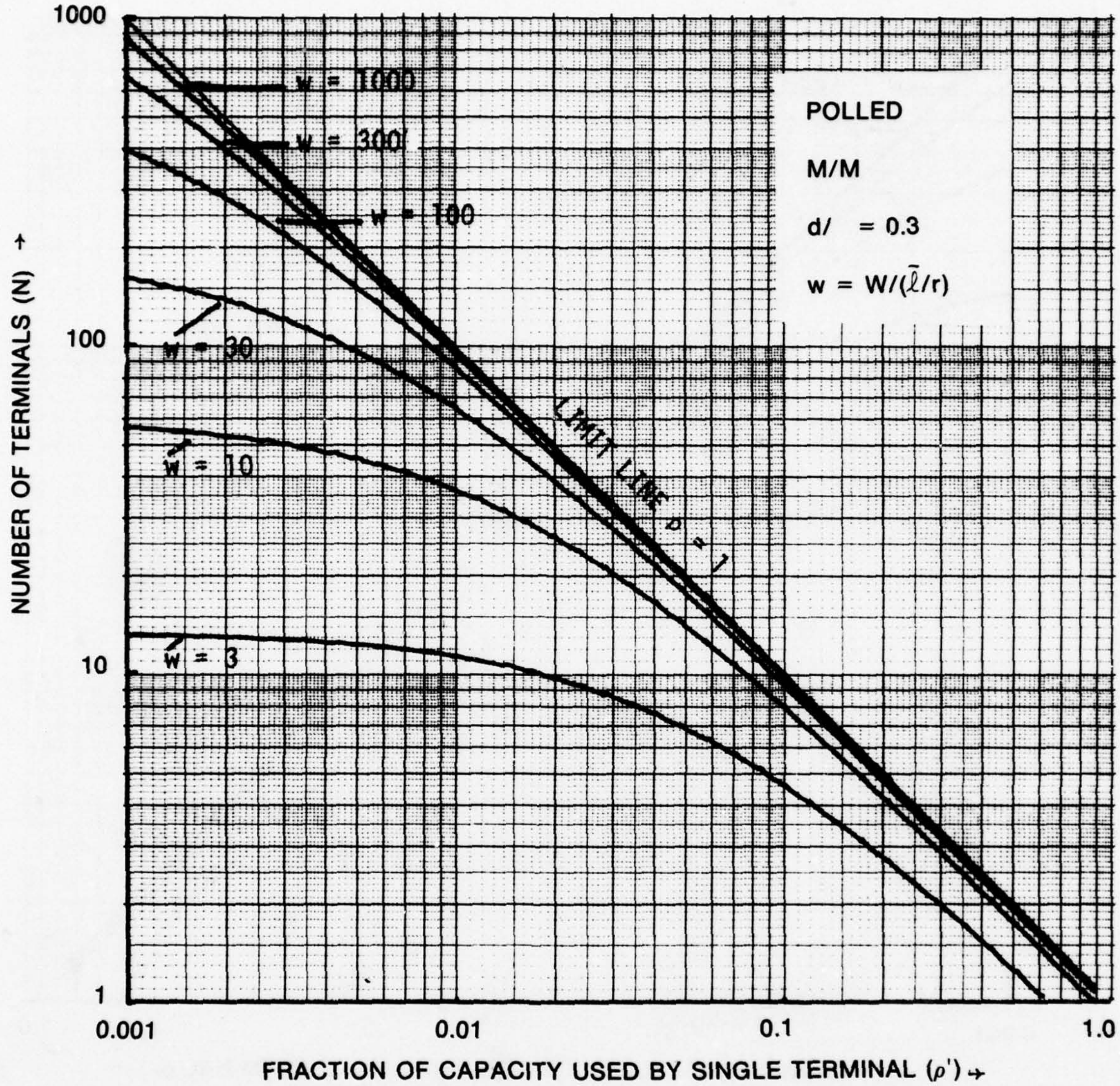


Figure B-18. Polled System Waiting Time (w) for Random Length Messages with Random Arrivals (Equation B-37) for $d/\bar{\ell} = 0.3$.
w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

For a typical value of $a/\bar{\ell}$ of 0.01, the optimum value of $b/\bar{\ell}$ is 0.14 and $\overline{m}$ is 7.58. A constant waiting time plot in the N vs ρ' plane is shown in figure B-19.

B.4.3.5 Reservation Assignment.

In reservation assignment, the message channel is shared between all users. Users make a reservation for the channel for each message for the length of time required to transmit

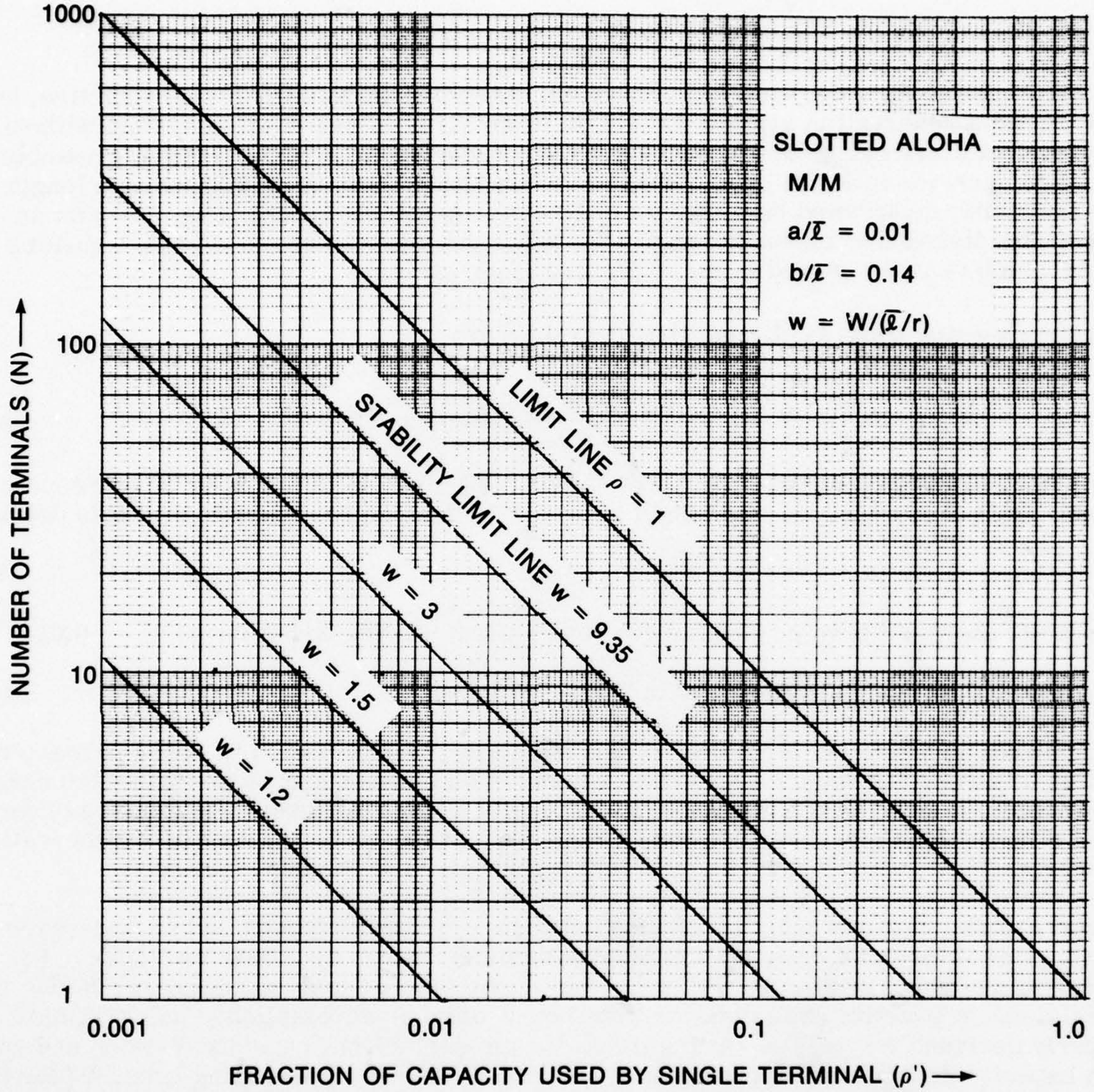


Figure B-19. Slotted ALOHA System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-41). w = Normalized System Waiting Time in Message Lengths = W/($\bar{\ell}$/r).

that message. Each message is held in a buffer at the user's terminal until the time reserved for its transmission. All the user buffers together act as a single virtual queue. There is no contention on the message channel and the message channel is shared to the full theoretical limit. In addition to the message channel, an orderwire or reservation channel is required in order to make reservations for the use of the message channel. The reservation messages are fixed length with random arrival times. The waiting times for messages of this type are covered in paragraph B.4.2. The two types of access which are applicable for the orderwire messages are synchronous time division multiple access (TDMA) and slotted ALOHA. We

shall investigate reservation assignment with a TDMA orderwire and with a slotted ALOHA orderwire after first considering reservation assignment without an orderwire.

B.4.3.5.1 Reservation Assignment Without an Orderwire

In any real system an orderwire or reservation channel is required. It is instructive, however, to investigate a reservation system without an orderwire. A reservation system without an orderwire is a classical M/M/1 queuing system. However, in a real system a preamble is required for carrier lock, bit sync, character sync, etc. Thus, the total message length is not exponentially distributed but consists of the fixed preamble length of a_1 bits plus an exponentially distributed message length of ℓ bits. This fits the class of M/G/1 queuing systems which is well covered in the literature (reference 1).

The system waiting time, W, for an M/G/1 system is

$$W = \frac{\bar{\ell}}{r}\frac{\alpha}{2}\left(\frac{2 - \alpha N\rho'(1 - 1/\alpha^2)}{1 - \alpha N\rho'}\right), \qquad \text{(B-42)}$$

where ρ' is the single-terminal utilization factor ($\lambda'\bar{\ell}/r$), N is the number of sources or terminals, $\bar{\ell}$ is the mean message length in bits, r is the channel bit rate, and α is defined by

$$\alpha = 1 + a_1/\bar{\ell} \;. \qquad \text{(B-43)}$$

Figure B-20 shows an N vs ρ' plot for constant system waiting times for $a_1/\bar{\ell} = 0.01$.

B.4.3.5.2 Reservation Assignment With TDMA Orderwire

An orderwire must be used for a real reservation assignment system in order to make reservations. With distributed control, the transmission of a request on an orderwire channel automatically adds the user's message to the virtual queue. All users monitor the orderwire channel and add each message duration to their copy of the queue length as the reservations are received. A control channel is therefore not required, in theory at least.

The total channel capacity must be divided between a message channel and an orderwire channel. This division of capacity can be accomplished either by FDMA or TDMA. For purposes of analysis, FDMA division will be assumed with no loss in total capacity due to this division. In practice, this division would most often be accomplished using TDMA. With a properly designed frame, the waiting times for an ideal FDMA capacity division and an ideal TDMA capacity division are approximately the same. The system waiting time, W, for this system is the sum of the mean waiting time on the orderwire channel to make a reservation (ie, to get a message entered into the virtual queue) plus the mean system waiting time for the message after it has entered the virtual queue. This is given by

$$W = \frac{\bar{\ell}}{r}\left\{\frac{\alpha}{2(1 - \theta)}\left[\frac{2 - \alpha N\rho'(1 - 1/\alpha^2)/(1 - \theta)}{1 - \alpha N\rho'/(1 - \theta)}\right] + \frac{\gamma}{\theta}\left[\frac{N/2}{1 - \frac{\gamma}{\theta}N\rho'} + 1\right]\right\} \qquad \text{(B-44)}$$

where α, $\bar{\ell}$, γ, N and ρ' are as defined in paragraph B.4.3.5.1, θ is the fraction of the total channel bit rate capacity devoted to the orderwire function, and γ is given by

$$\gamma = a_2/\bar{\ell} \;, \qquad \text{(B-45)}$$

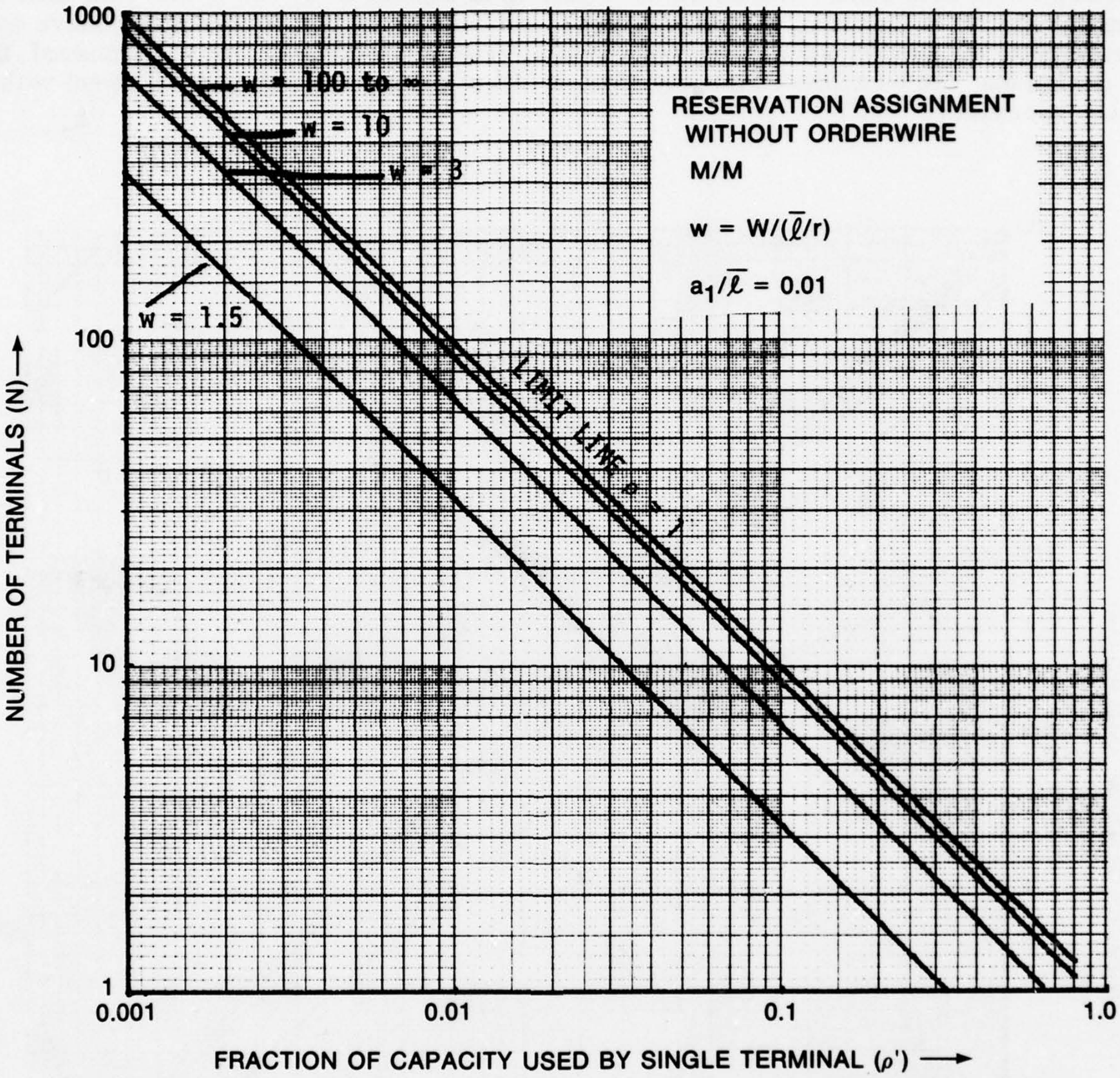


Figure B-20. Reservation Assignment System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-42) Without Orderwire for $a_1/\overline{\ell} = 0.01$. w = Normalized System Waiting Time in Message Lengths = $W/(\overline{\ell}/r)$.

where a_2 is the number of bits in a single reservation message. The system waiting time is affected by the division of the total channel capacity between the message channel and the orderwire channel. An empirical equation for the optimum division in terms of θ is given by

$$\theta\Big|_{\text{optimum}} \simeq 0.227 \log_{10} N(1 - a_1/\overline{\ell} - a_2/\overline{\ell} - N\rho') + a_2/\overline{\ell}. \qquad \text{(B-46)}$$

Using this value of θ in equation B-44, the constant waiting time N vs ρ' curves for reservation assignment with TDMA orderwire were plotted in figures B-21 and B-22. Note that the optimum value of θ has been picked for each N and each ρ', so that a constant w curve does not represent the performance of any one system. The curves do represent, in general, the best design that can be achieved for any given N and ρ' using reservation assignment with a TDMA orderwire.

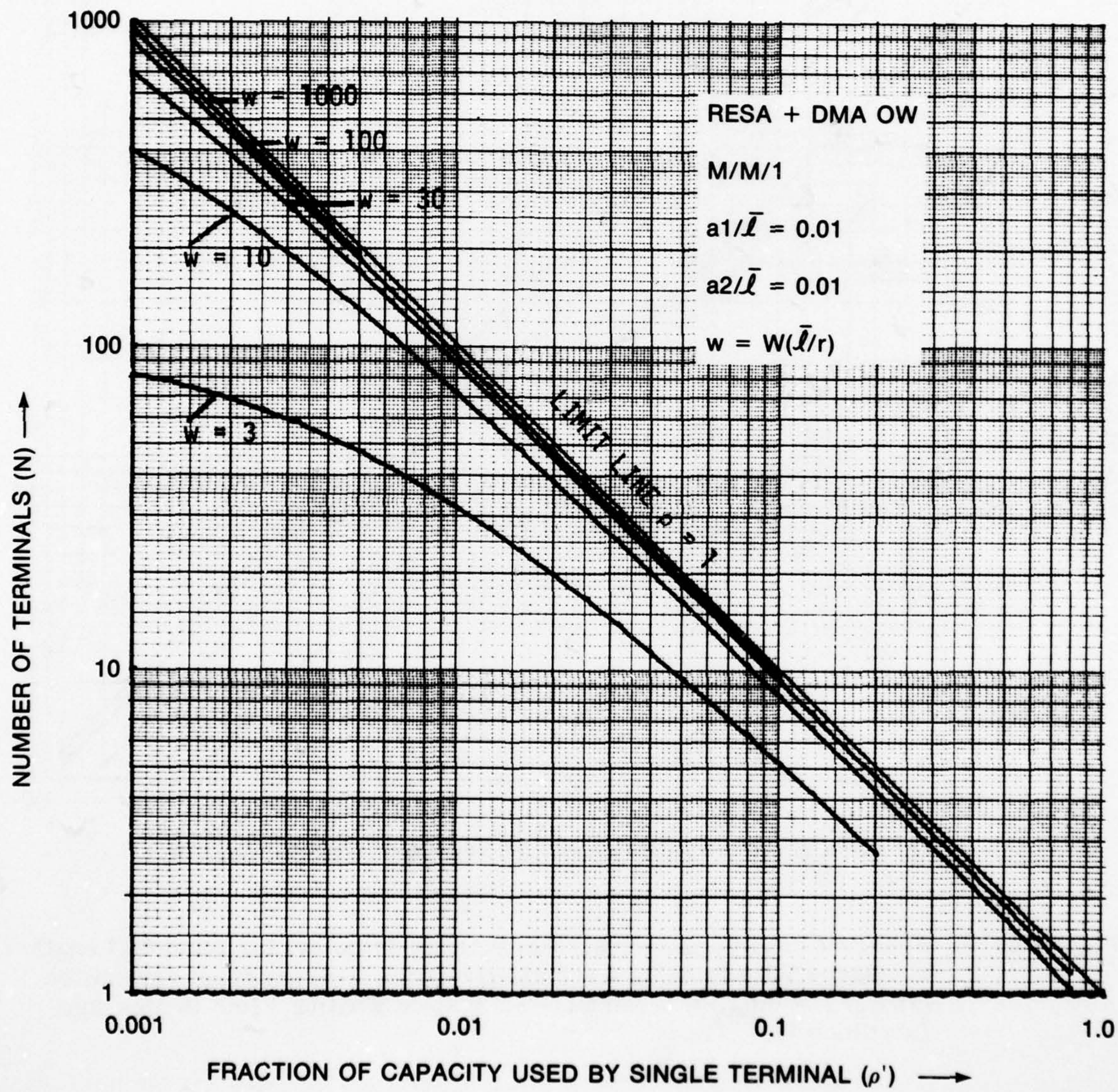


Figure B-21. Reservation Assignment System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-44) for TDMA Orderwire With $a_1/\bar{\ell}$ and $a_2/\bar{\ell}$ = 0.01, Using Optimum θ. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

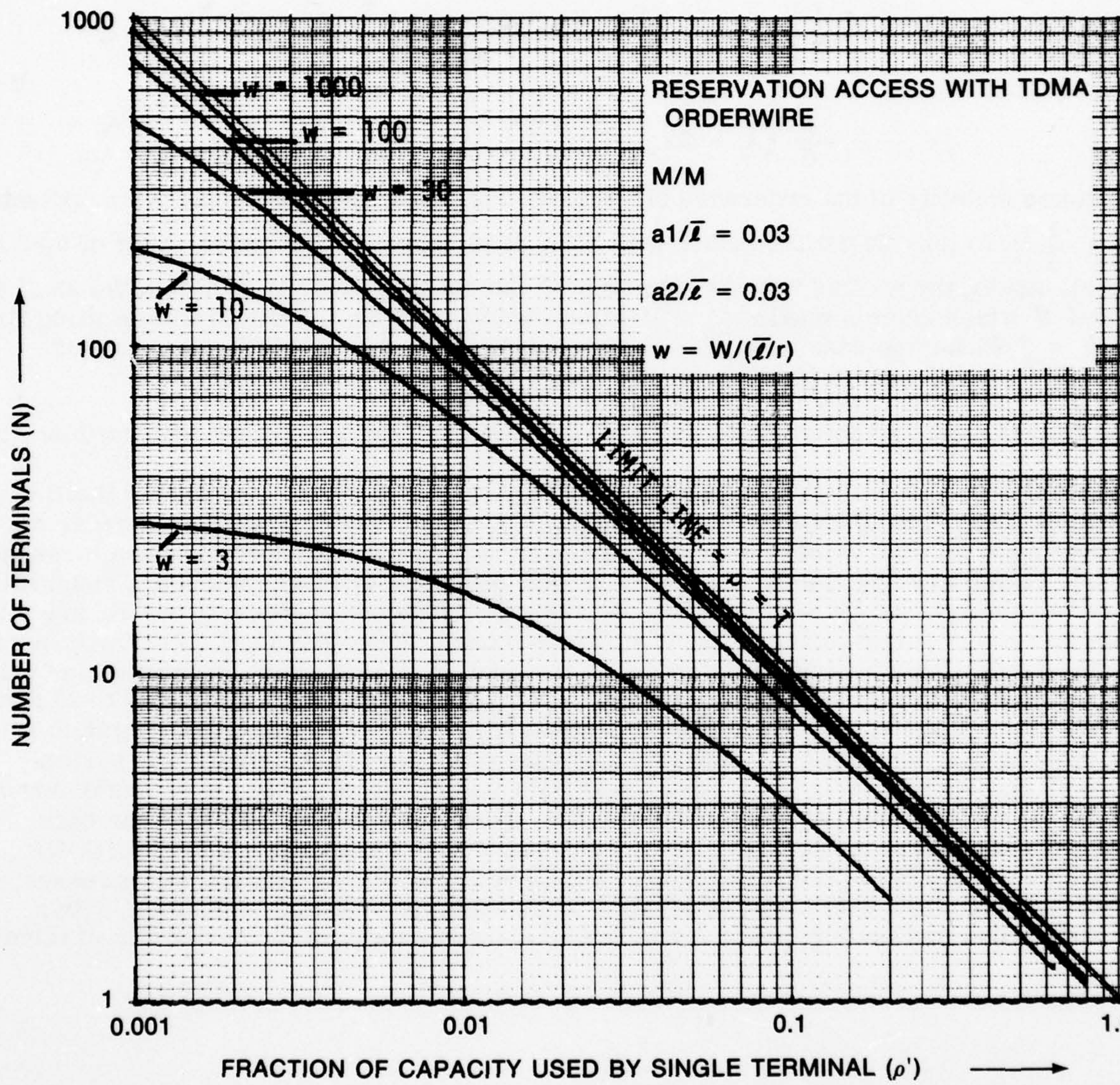


Figure B-22. Reservation Assignment System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-44) for TDMA Orderwire With $a_1/\bar{\ell}$ and $a_2/\bar{\ell}$ = 0.03, Using Optimum θ. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

B.4.3.5.3 Reservation Assignment With Slotted ALOHA Orderwire

Slotted ALOHA can be used for the orderwire of a reservation assignment system. Using the same notation as in paragraph B.4.3.5.2, and using the waiting time, W_2, on the orderwire circuit given by equation B-26, we obtain

$$W = \frac{\bar{\ell}}{r}\left\{\frac{a}{2(1-\theta)}\left[\frac{2 - aN\rho'(1 - 1/a^2)/(1-\theta)}{1 - aN\rho'/(1-\theta)}\right] + \frac{\gamma}{\theta}\left[1 + 32\left(\frac{\gamma}{\theta}N\rho'\right)^{3/2}\right]\right\}. \tag{B-47}$$

To guarantee stability of the orderwire circuit, restrict the value of the orderwire utilization factor, $(\frac{\gamma}{\theta}\rho)$, to less than 0.20, rather than allow it to approach theoretical limit of 0.36 (reference 2). Again, the waiting time is a function of the channel capacity division. We shall pick a value of θ which gives a maximum utilization factor, ρ, at an infinite system waiting time. Using $\theta = 0.05$ for the case of $a_1/\bar{\ell} = a_2/\bar{\ell} = 0.01$, and $\theta = 0.125$ for the case of $a_1/\bar{\ell} = a_2/\bar{\ell} = 0.03$, gives the N vs ρ' plots shown in figures B-23 and B-24.

B.4.3.6 Comparison of Access Systems for Messages With Random Length and Random Arrivals

The results of the previous paragraphs can be compared most clearly by plotting the N vs ρ' curves for a fixed waiting time for all candidate systems on the same graph. In order to do this, we must assume values of the preamble plus guard time length (a_1), mean message length ($\bar{\ell}$), TDMA and ALOHA block length (b), total delay in a polling system (d), reservation message length (a_2), and bit rate capacity division (θ). The parameters, b and θ, are picked to optimize system performance as previously discussed. The other parameters will be picked to be typical values for practical systems. To this end we shall assume the parameter values shown in table B-3 in making the comparisons. The results are shown in figures B-25 through B-28. The area of the N vs ρ' plane in which each type access system gives minimum system waiting time is shown in figure B-29. These are the optimum areas only for the system parameters specified in table B-3. Note that FDMA and TDMA give very poor performance except for the case of very few terminals with large channel utilization factors for each terminal. Over most of the N vs ρ' plane, reservation assignment with a slotted ALOHA orderwire gives minimum waiting time. As the allowable system waiting time increases, reservation assignment with a slotted ALOHA orderwire, reservation assignment with a TDMA orderwire, and polling systems can handle approximately the same number of terminals.

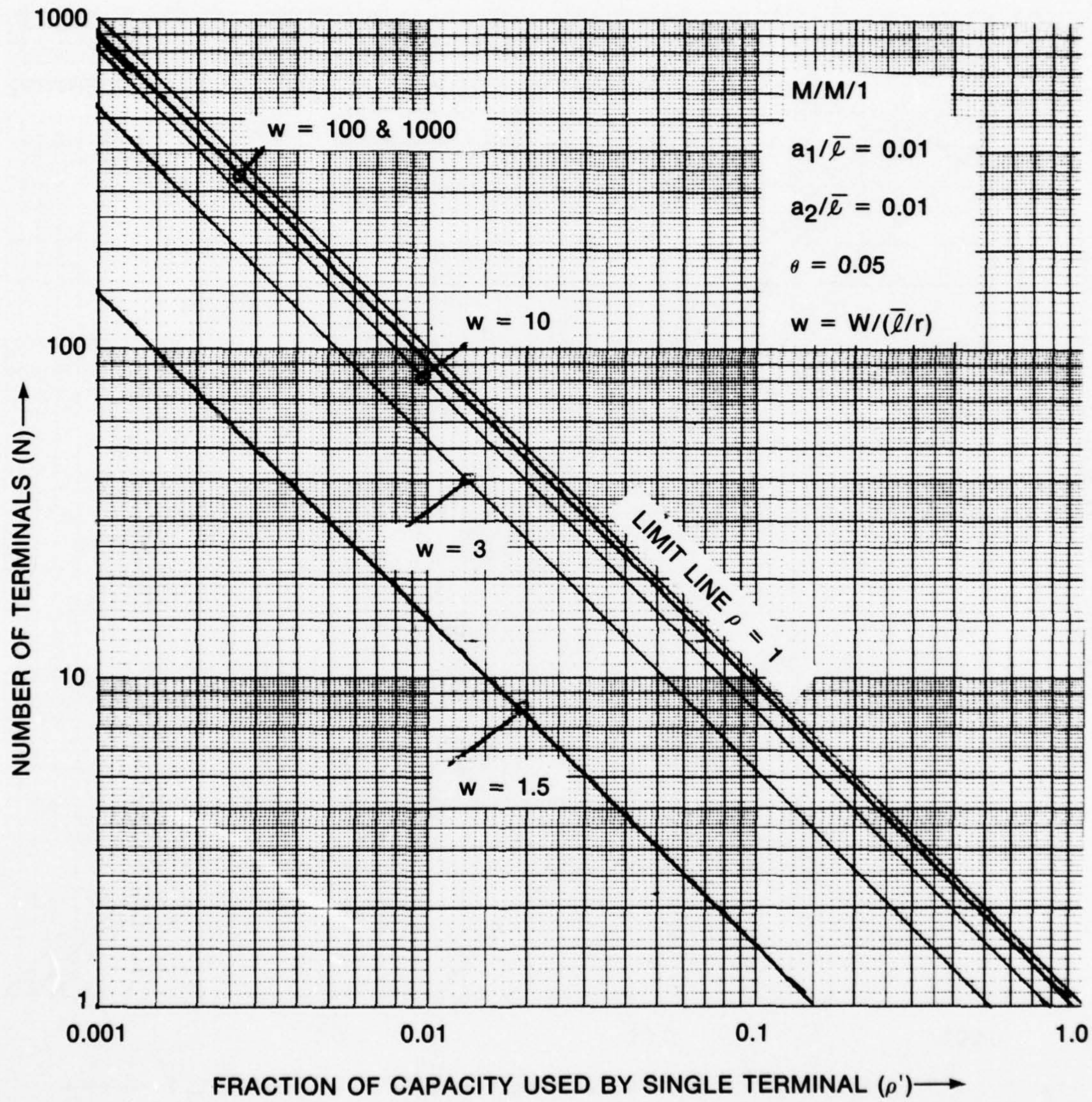


Figure B-23. Reservation Assignment System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-47) for Slotted ALOHA Orderwire With $a_1/\bar{\ell}$ and $a_2/\bar{\ell}$ = 0.01 and θ = 0.05. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

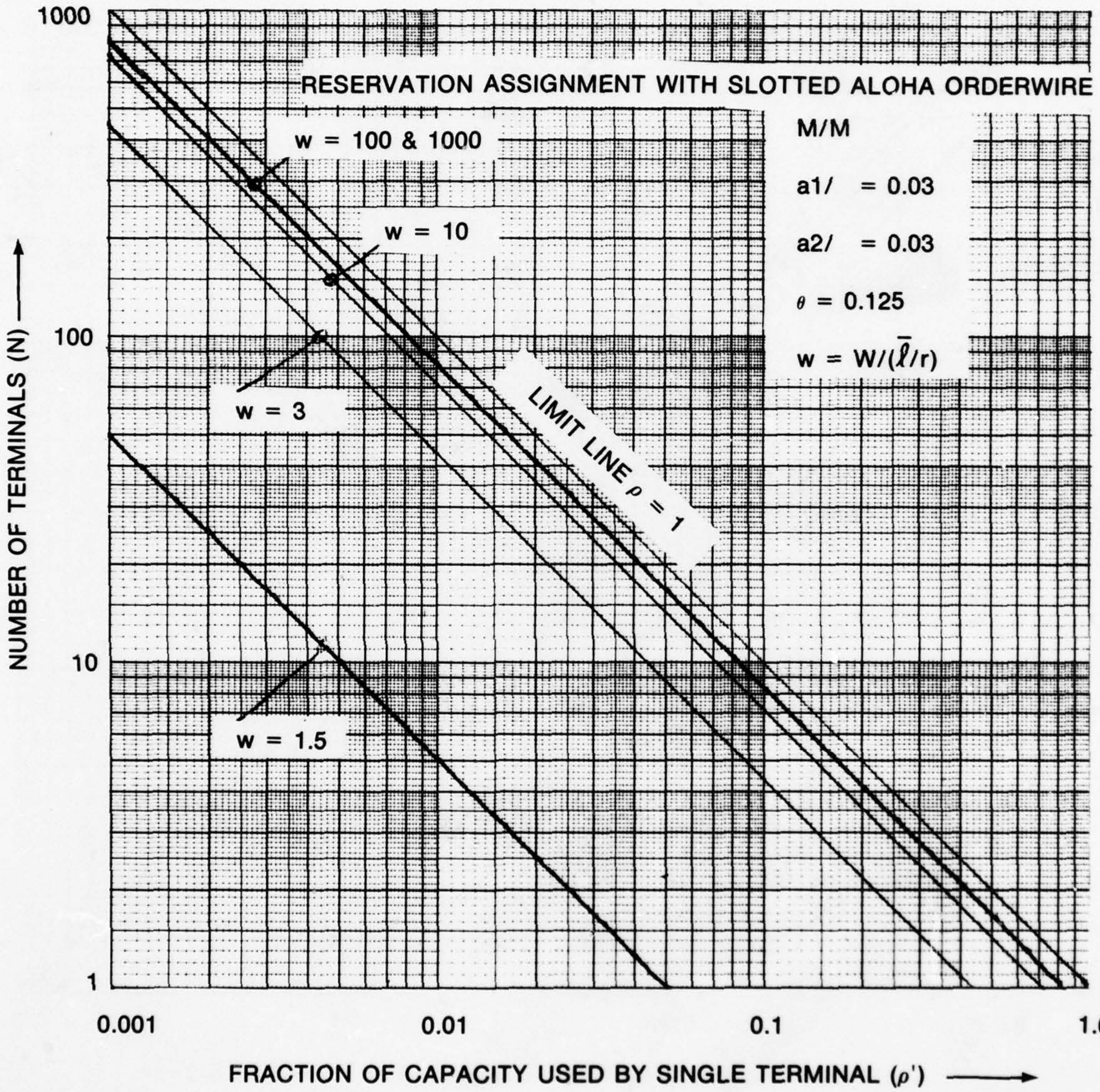
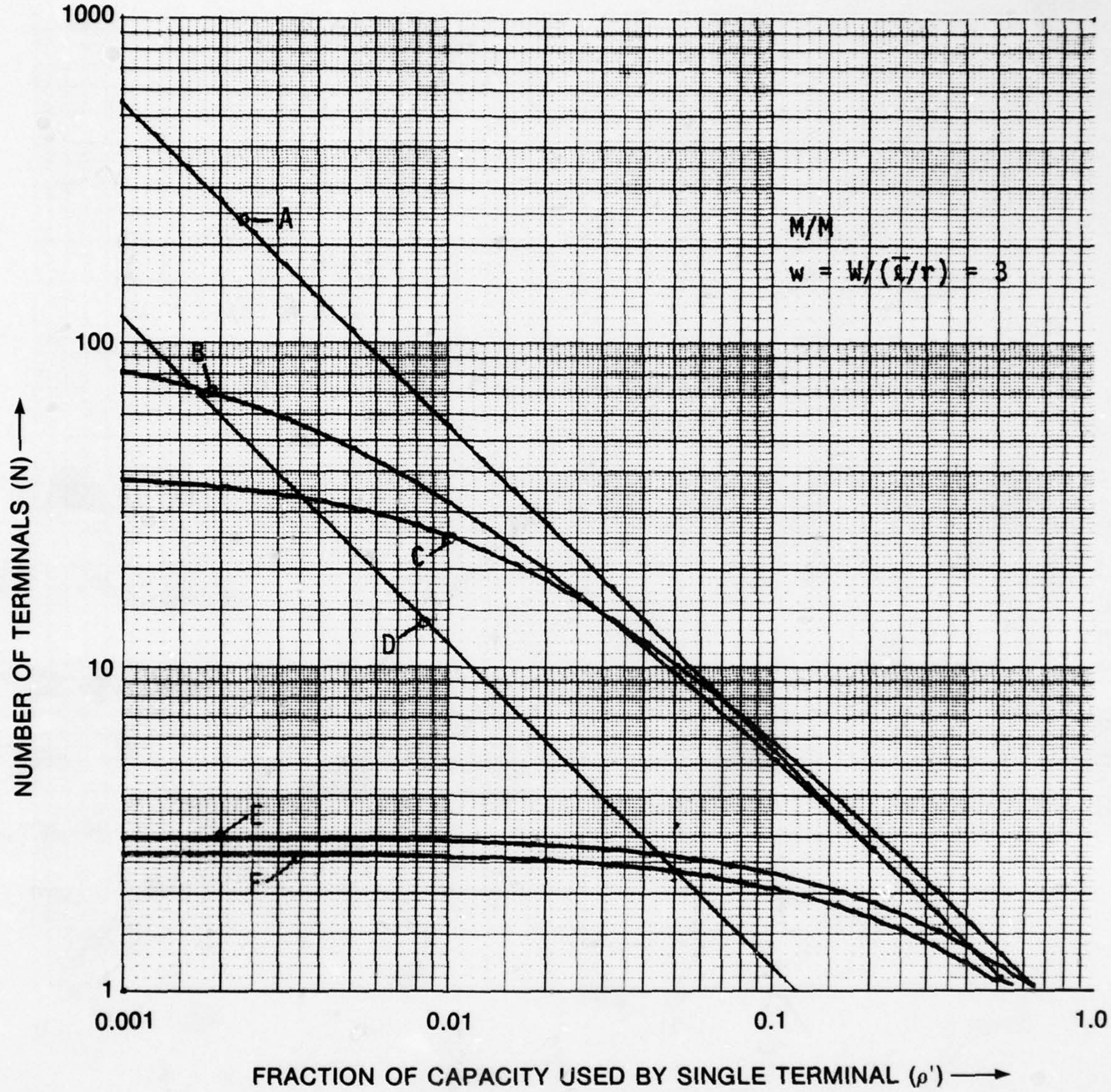


Figure B-24. Reservation Assignment System Waiting Time (w) for Random Length Messages With Random Arrivals (Equation B-47) for Slotted ALOHA Orderwire With $a_1/\bar{\ell}$ and $a_2/\bar{\ell}$ = 0.03 and θ = 0.125. w $\equiv$ Normalized System Waiting Time in Message Lengths = $W/\bar{\ell}/r$).



LEGEND		
CURVE	TYPE SYSTEM	EQ. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED	B-37
D	SLOTTED ALOHA	B-41
E	FDMA	B-32
F	TDMA	B-34

Figure B-25. Comparison of Systems for w = 3 for Random Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

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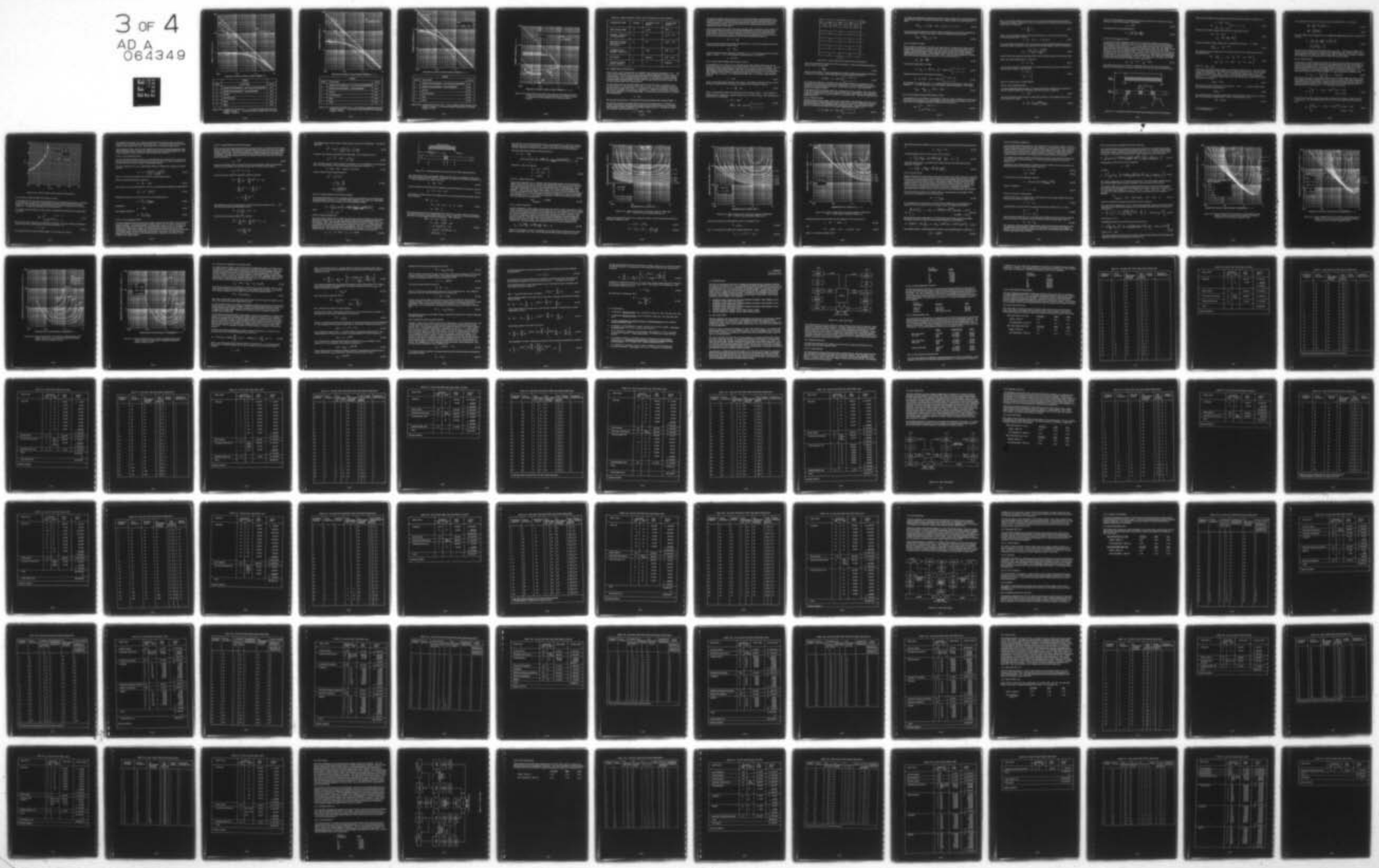

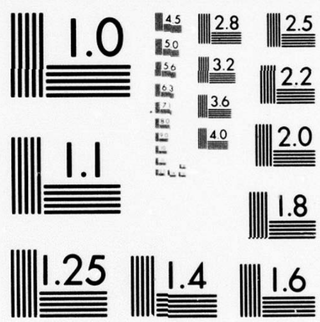

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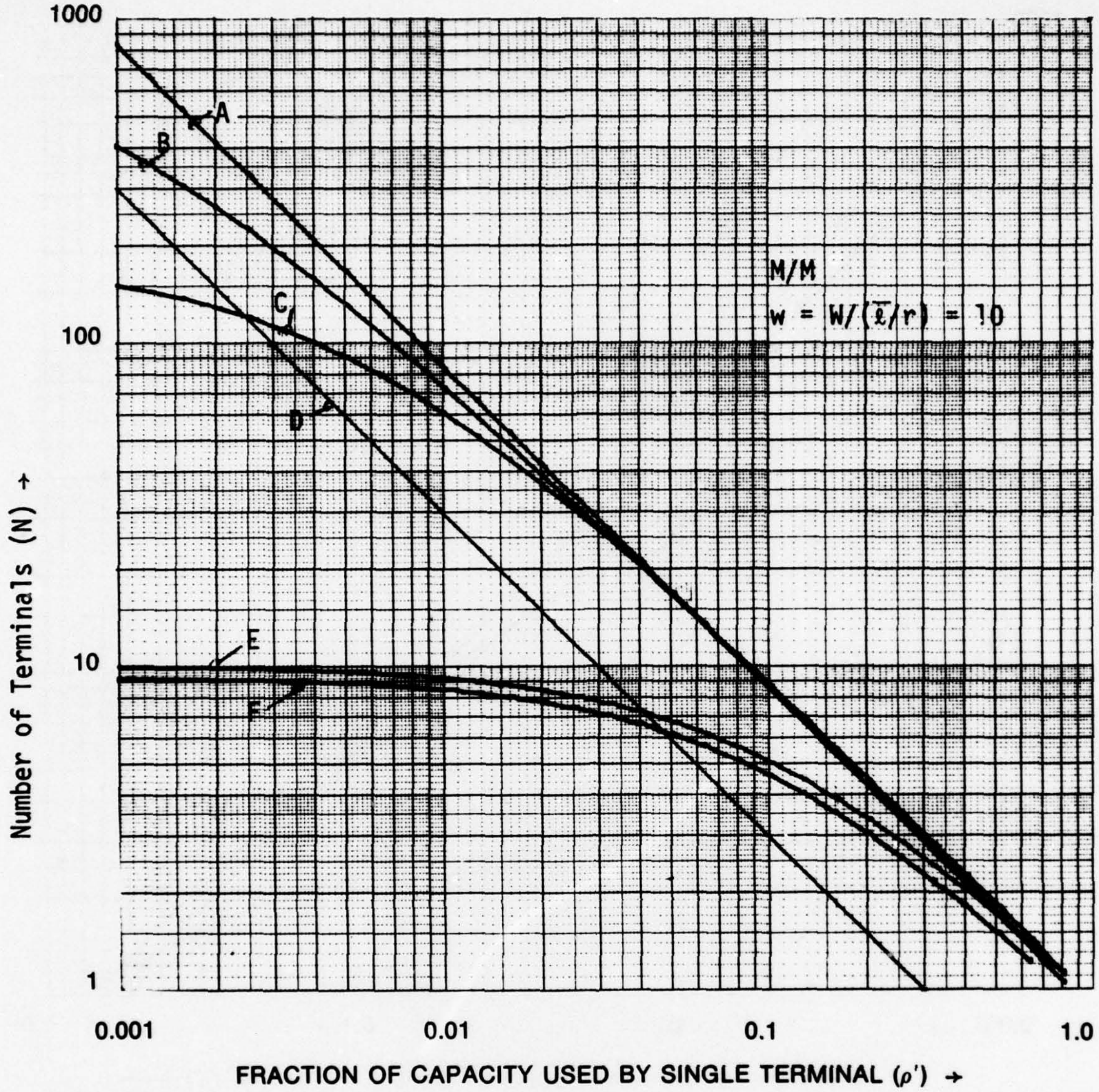
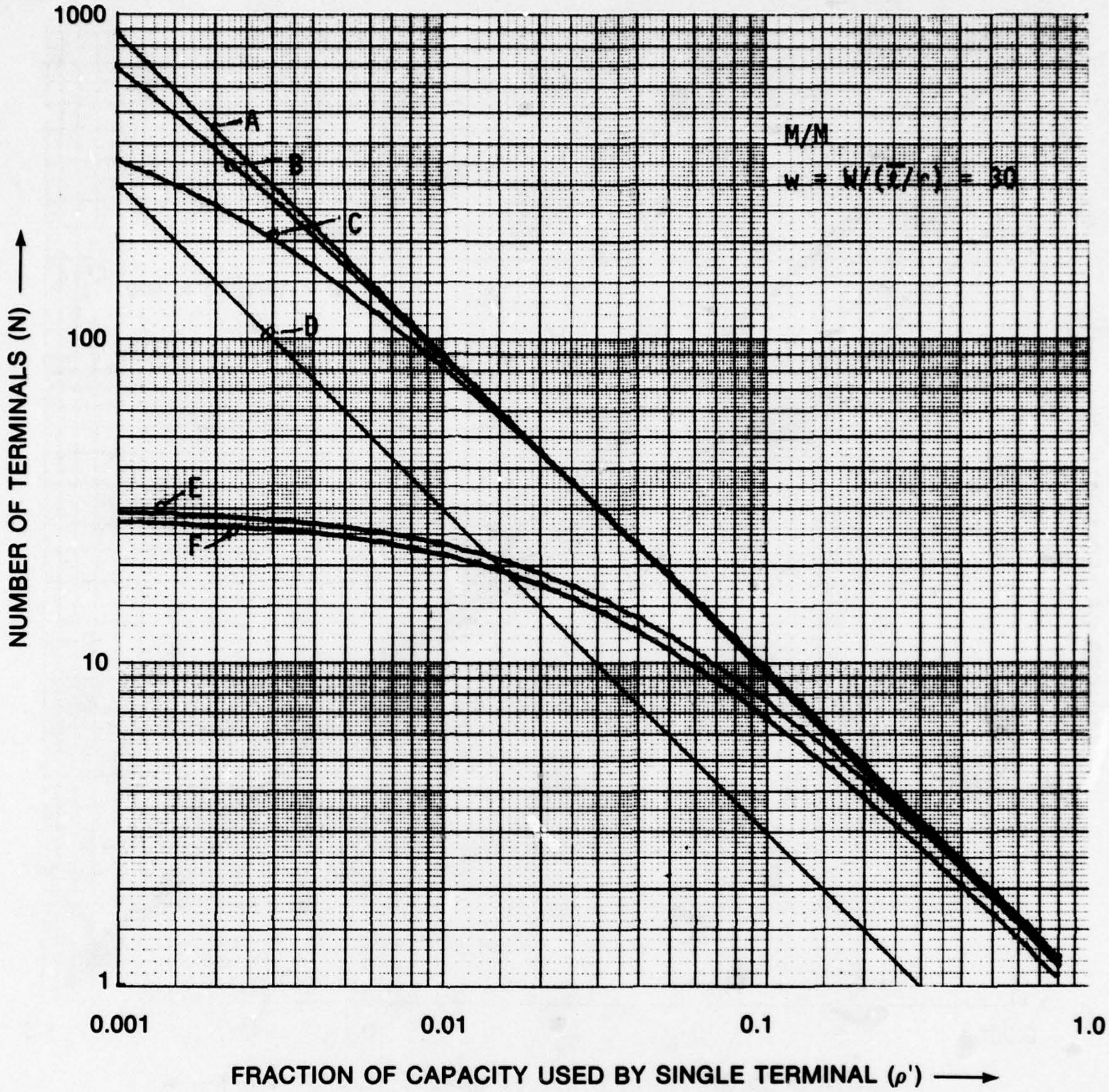


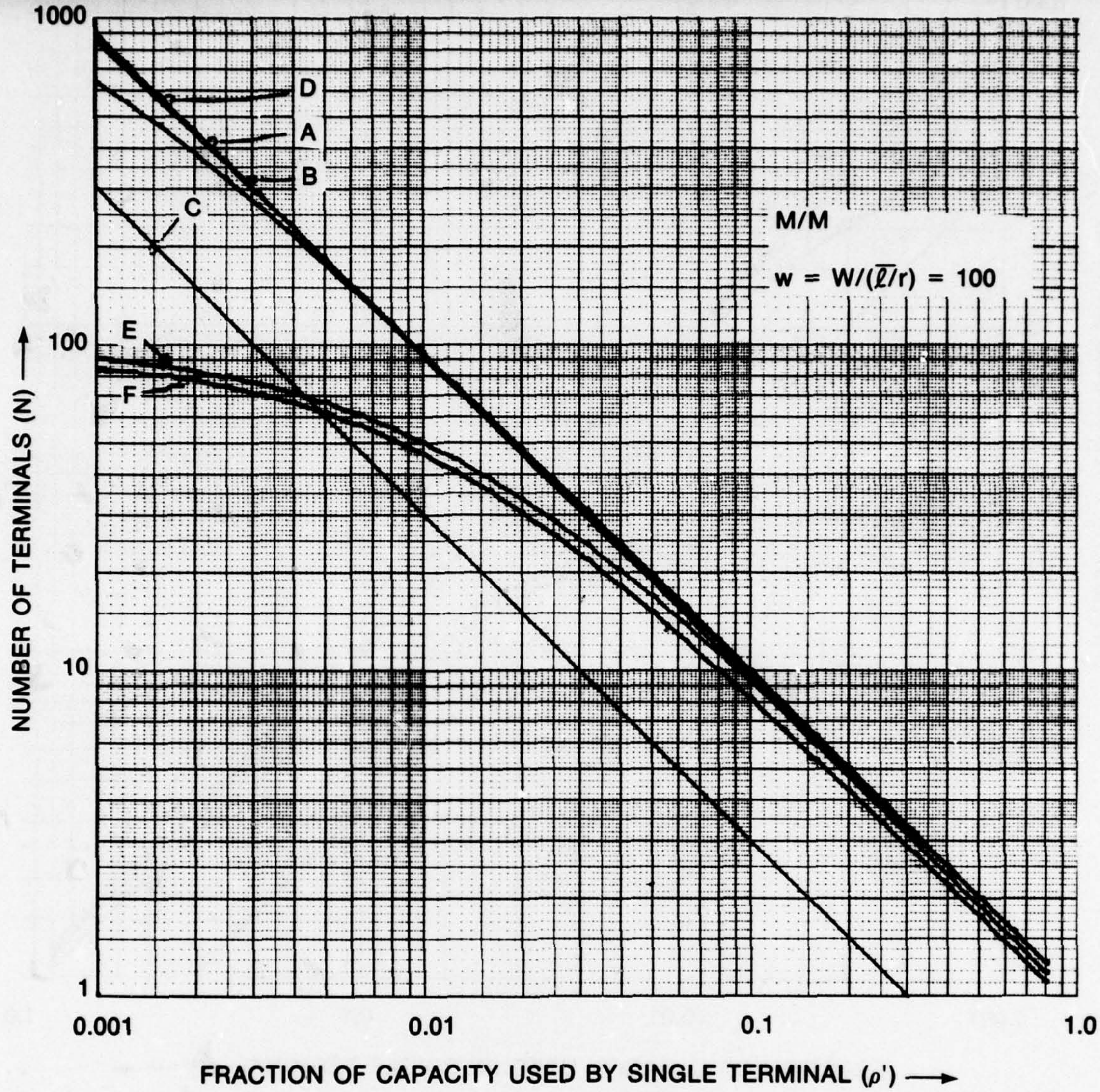
	LEGEND	
CURVE	TYPE SYSTEM	EQ. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED	B-37
D	SLOTTED ALOHA	B-41
E	FDMA	B-32
F	TDMA	B-34

Figure B-26. Comparison of Systems for $w = 10$ for Random Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.



LEGEND		
CURVE	TYPE SYSTEM	EQ. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED	B-37
D	SLOTTED ALOHA	B-35
E	FDMA	B-32
F	TDMA	B-34

Figure B-27. Comparison of Systems for $w = 30$ for Random Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.



LEGEND		
CURVE	TYPE SYSTEM	EQ. NO.
A	RESERVATION ASSIGNMENT + SLOTTED ALOHA ORDERWIRE	B-47
B	RESERVATION ASSIGNMENT + TDMA ORDERWIRE	B-44
C	POLLED	B-37
D	SLOTTED ALOHA	B-41
E	FDMA	B-32
F	TDMA	B-34

Figure B-28. Comparison of Systems for w = 100 for Random Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $\bar{W}/(\bar{\ell}/r)$.

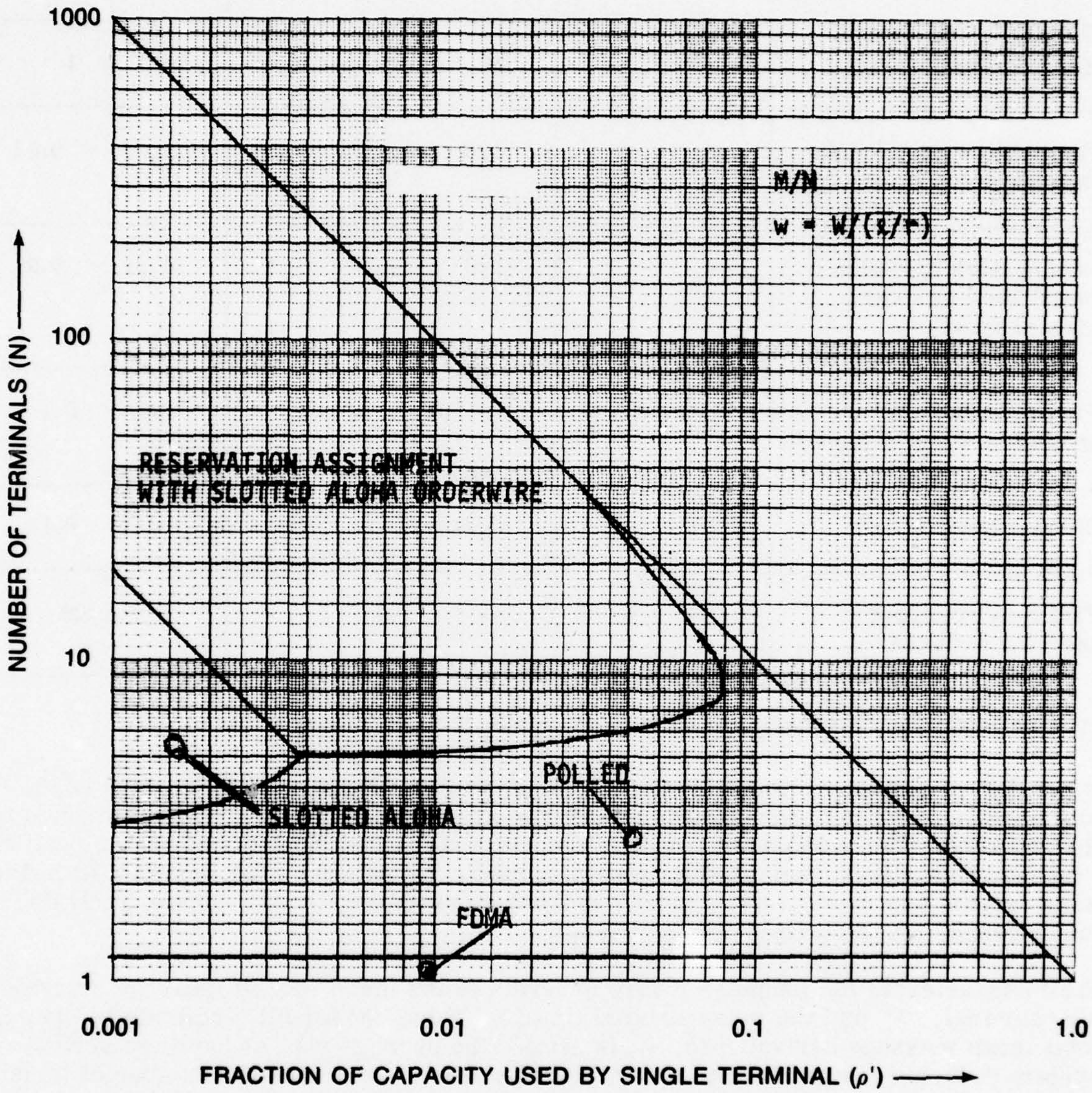


Figure B-29. Areas in Which Each Type Access System Gives Minimum System Waiting Time for Random Length Messages With Random Arrivals. w = Normalized System Waiting Time in Message Lengths = $W/(\bar{\ell}/r)$.

Table B-3. System Parameter Values Used in Comparisons of Access Systems.

PARAMETER NAME	SYMBOL	ASSUMED VALUE (BITS)	NORMALIZED VALUE
Mean message length	$\bar{\ell}$	12,000	$\bar{\ell}/\bar{\ell} = 1$
Preamble + guard time on message channel	a_1	120	$a_1/\bar{\ell} = 0.01$
Reservation message + guard time on order-wire channel	a_2	120	$a_2/\bar{\ell} = 0.01$
Propagation delay + preamble + guard time	d	1,200	$d/\bar{\ell} = 0.1$
Block length	b	Optimum	$b/\bar{\ell} = 0.14$
Fraction of capacity used for orderwire	θ	---	Optimum

B.5 DERIVATION OF EQUATIONS

Many results on system waiting time are available in the literature (references 1, 2, 3, and 5). In most cases it has been necessary to modify the available equations to fit those cases to be considered here. The necessary additional derivations or modifications of system waiting time expressions will be presented in this paragraph. We will consider systems with fixed message lengths and deterministic arrivals, fixed message length and random arrivals, and random message lengths with random arrivals.

We shall characterize the message traffic in terms of the mean rate of message arrivals from a terminal, λ', and the mean service time, $\bar{x}$. If the λ' for all terminals is the same, the total mean message arrival rate, λ, is simply the average rate of message arrivals into the system in messages per second and is given by $N\lambda'$, where N is the number of terminals. The message duration, x, is the message length, ℓ, in bits divided by the bit rate, r, at which data is transmitted.

$$x = \ell/r$$

The message service time, x, is therefore directly proportional to the message length, ℓ.

We shall be particularly concerned with the mean system waiting time, W. It will be convenient in many cases to normalize this waiting time to the time it would take to transmit a mean message of length $\bar{\ell}$ using the full channel capacity bit rate, r. We therefore define the normalized mean waiting time, w, as

$$w = W/(\bar{\ell}/r) = W/\bar{x}.$$

The primary function of this paragraph is to present the existing results of queuing theory as applied to satellite communication in such a way that the various queuing systems can be readily compared. To this end, simplified approximate models will be used as necessary to clarify the presentation. We have borrowed from the existing literature extensively, as indicated in the list of references.

Several statements can be made concerning a queuing system, regardless of the statistics of the message arrivals and the service rate and independence of the type of queuing system being studied. Let $\bar{x}$ be the mean transmission or service time of a message, and let W_q be the mean message time in queue. Then the mean total waiting time, W, in the system is the sum of the mean transmission time plus the mean waiting time in queue, or

$$W = \bar{x} + W_q.$$

If L_q is the mean number of messages in the queue and λ is the mean message arrival rate from all sources, then by Little's result,

$$L_q = \lambda W_q.$$

If all N terminals generate messages at the same rate, λ', and have the same mean message length, $\bar{\ell}$, then $\lambda = N\lambda'$ and the channel utilization factor, ρ, is given by

$$\rho = N\lambda'\bar{\ell}/r.$$

B.5.1 Fixed Length Messages With Periodic Arrivals

In paragraph B.5.1, we will derive the equations for the mean system waiting time, W, for those cases where the messages are of a fixed length of ℓ bits and arrive periodically. We will consider the TDMA-FDMA system in which there are M separate frequency channels, with each frequency channel divided into m time slots of n bits each per frame and serving N users. This multiple access structure is diagrammed in figure B-30 showing n bits in each TDMA burst and k bits in a frame. It is assumed that the bit rate, r', of a single FDMA channel is given by

$$r' = r/M, \tag{B-48}$$

where r is the total channel capacity of the system. The number of data bits of delay, d, from the start of transmission of a message to completion of the message is given by

$$d = n + \left(\frac{\ell}{n} - 1\right)k, \tag{B-49}$$

where n is the number of bits in the first burst of the message, and $\frac{\ell}{n} - 1$ is the number of additional frames required to complete transmission of an ℓ bit message. The transmission or service time, x, is therefore

$$\begin{aligned} x &= d/r' = Md/r \\ &= \frac{M}{r}\left[n + \left(\frac{\ell}{n} - 1\right)k\right] \quad \text{for} \begin{cases} 1 \le M \le N \\ 1 \le n \le \ell \end{cases} \end{aligned} \tag{B-50}$$

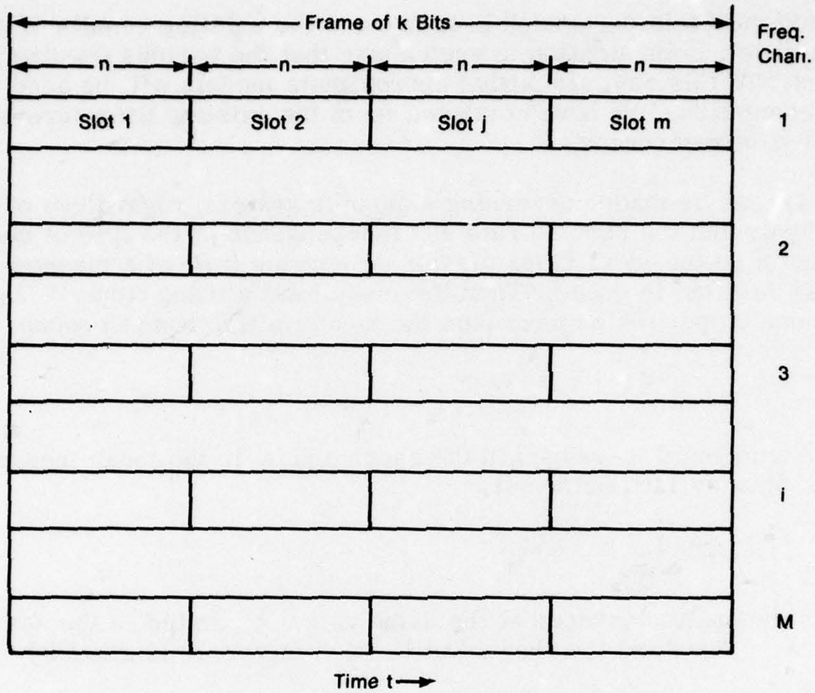


Figure B-30. TDMA-FDMA Access Structure for D/D Systems.

where it is assumed for simplicity that ℓ/n is an integer. It will be noted that the number of bits per frame, k, is given by

$$k = \frac{N}{M} n, \tag{B-51}$$

where N is the number of users or channels in the TDMA-FDMA frame structure and N/M is assumed to be an integer. Substituting equation B-51 into equation B-50 gives

$$x = \frac{1}{r} \left[n(M - N) + \ell N \right] \text{ for } \begin{cases} 1 \leq M \leq N \\ 1 \leq n \leq \ell \end{cases}. \tag{B-52}$$

Two cases are of interest. In the first case, the message arrives for transmission at the instant the time slot becomes available for transmission so that the message does not wait in a queue for message transmission to start. In this case, W_q is zero. This case will be referred to as phased arrivals.

In the second case, the messages arrive for transmission at some arbitrary time in the frame so that the message may have to wait in queue for the start of transmission. The waiting time in queue is assumed to be a random variable in an ensemble sense. This will be referred to as unphased arrivals.

B.5.1.1 Phased Arrivals

In phased arrivals, the messages arrive at the same instant as the beginning of the time slot in which transmission of that message can start. In this case, there is no waiting time in queue until the transmission of the beginning of the message can start. The total system waiting time, W, is therefore just equal to the message transmission time lapse, x, or

$$W = \frac{1}{r} \left[n(M - N) + \ell N \right] \quad \text{for} \begin{cases} 1 \leq M \leq N \\ 1 \leq n \leq \ell \end{cases}. \tag{B-53}$$

It is clear from inspection of equation B-53 that the system waiting time is minimized first by minimizing the number of frequency channels (M). Setting M equal to its minimum value of 1 gives

$$W\Big|_{M = 1} = \frac{1}{r}[\ell N - n(N - 1)] \text{ for } 1 \leq n \leq \ell. \tag{B-54}$$

It is now clear from equation B-54 that the system waiting time can be further minimized by setting the number of bits per time slot, n, equal to its maximum value, ℓ, so that

$$W_{min} = W\Big|_{\substack{M = 1 \\ n = \ell}} = \ell/r. \tag{B-55}$$

B.5.1.2 Unphased Arrivals

If the arrivals are unphased to the time slots, there will be a waiting time in queue from the time that the message arrives until the start of the time slot in which transmission can be started. While the message arrivals in any one system are fixed and periodic, they may be random in an ensemble sense. Assume that the message arrival time is random with an equal likelihood of arriving at any time within a frame. Then the mean waiting time in queue before this message transmission can start is 1/2 the frame duration, or

$$W_q = \frac{k}{2r'} = \frac{Mk}{2r}. \tag{B-56}$$

The system waiting time, W, is then

$$W = W_q + x = \frac{M}{r}\left[n + (\frac{\ell}{n} - 1/2)k\right] \text{ for } \begin{cases} 1 \leq M \leq N \\ 1 \leq n \leq \ell \end{cases}. \tag{B-57}$$

Substituting equation B-51 into equation B-57 gives

$$W = \frac{1}{r}\left[n(M - N/2) + \ell N\right] \text{ for } \begin{cases} 1 \leq M \leq N \\ 1 \leq n \leq \ell \end{cases}. \tag{B-58}$$

By inspection it is noted that, for $N > 1$, equation B-58 is minimized using a single FDMA channel ($M = 1$) and by choosing a time slot length as large as possible ($n = \ell$), so that

$$W_{min} = W\Big|_{\substack{M = 1 \\ n = \ell}} = \frac{\ell}{r}[1 + N/2]. \tag{B-59}$$

B.5.2 Fixed Length Messages With Random Arrivals

In paragraph B.5.2 we will derive the equations for the mean system waiting time, W, for those cases where the messages are of a fixed length of ℓ bits and where the message arrivals are random with an exponential distribution of interarrival time given by

$$f(t) = \begin{cases} 0 & \text{for } t < 0 \\ \lambda e^{-\lambda t} & \text{for } t \geq 0 \end{cases}. \tag{B-60}$$

Here λ is the mean message arrival rate, and t is the time duration between the arrival of successive messages. If there are N users or message sources, then the total mean message arrival rate, λ, is given by

$$\lambda = \sum_{i=1}^{N} \lambda_i , \tag{B-61}$$

where λ_i is the message arrival rate from the i^{th} source. If all sources have the same message generation rate, λ', then

$$\lambda = N\lambda' \quad (\text{if } \lambda_i = \lambda' \text{ for all i}). \tag{B-62}$$

The mean waiting time in queue, W_q, for any system with exponentially distributed message interarrival times, regardless of the distribution of message length, is given by (reference 1):

$$W_q = \frac{(\lambda \bar{x}) \; \bar{x} \left[1 + \sigma_b^2/\bar{x}^2\right]}{2\left[1 - (\lambda \bar{x})\right]}, \tag{B-63}$$

where $\bar{x}$ is the mean message transmission time and σ_b^2 is the variance in the service time.

Again, the system waiting time, W, is given by

$$W = \bar{x} + W_q. \tag{B-64}$$

For our present case, the message length, ℓ, is fixed so that the service time is fixed with a mean, $\bar{x}$, and a variance, σ_b^2, given by

$$\left.\begin{aligned} \bar{x} &= \ell/r' \\ \sigma_b^2 &= 0 \end{aligned}\right\} \tag{B-65}$$

where r' is the bit rate of a single channel.

B.5.2.1 Fixed Assignment FDMA

For fixed assignment FDMA systems, we assume that the total channel bit rate capacity of r bits per second is divided into N channels, each with a bit rate, r', given by

$$r' = r/N, \tag{B-66}$$

and that each of the N users occupies a single FDMA channel. From equations B-63, B-64, B-65, and B-66 we obtain

$$W = \frac{\ell}{r'} + \frac{\ell}{r'} \frac{\lambda' \ell/r'}{2\left[1 - \lambda' \ell/r'\right]}, \tag{B-67}$$

where it will be noted that λ in equation B-63 has been replaced by λ' since only a single user uses a single FDMA channel. Substituting

$$\rho' = \lambda' \ell / r \tag{B-68}$$

into equation B-67 and simplifying gives

$$W = \frac{\ell}{r} \frac{N}{2} \left[\frac{2 - N\rho'}{1 - N\rho'} \right] . \tag{B-69}$$

B.5.2.2 Fixed Assignment TDMA

A comparison of fixed assignment FDMA and fixed assignment TDMA message timing is shown in figure B-31. Establish a time axis for a TDMA user which starts at the beginning of a TDMA time slot for the user ($t = 0$). Assume that each time slot is n bits long, and that the number of bits between the beginning of adjacent time slots is Nn. The TDMA system utilizes the entire bit rate capacity of the system (r bits per second), while the FDMA system uses a bit rate per FDMA channel, r', of only $1/N^{th}$ of the total bit rate, as expressed in equation B-66. If the FDMA queue is empty when a new message arrives, transmission of that message will start immediately at a time designated t_{S1}. The transmission of the TDMA system cannot start until the beginning of the user's next time slot, at time t_{S2}. The FDMA message will end ℓ bits after the start at a time, t_{E1}, given by

$$t_{E1} = t_{S1} + \ell/r' = t_{S1} = N\ell/r. \tag{B-70}$$

The TDMA message will also end after a sufficient number of time slots have passed to transmit an ℓ bit message, at time t_{E2}. Since there are n bits per time slot and nN bits per

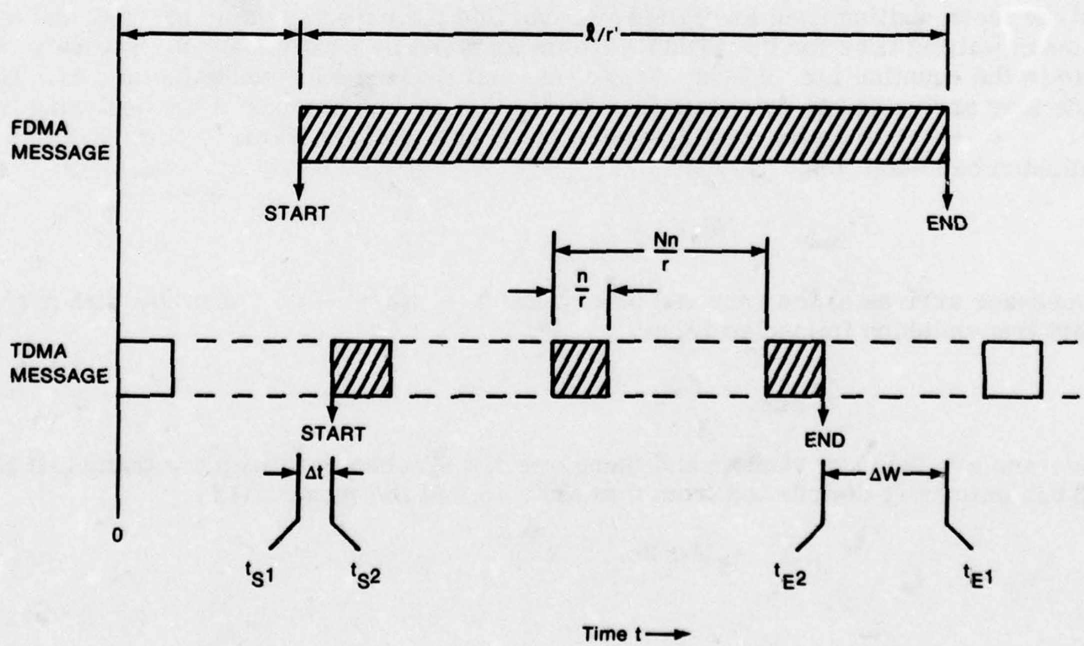


Figure B-31. Comparison of FDMA and TDMA Queue Waiting Time for M/D Systems.

frame, the total number of bits required before the end of the message is reached, k_T, is

$$k_T = \left.\begin{matrix} n + (\frac{\ell}{n} - 1)nN \\ \\ \ell N + n(1 - N) \end{matrix}\right\} \text{for } 1 \le n \le \ell. \tag{B-71}$$

The end of the TDMA message will therefore be at time t_E2, given by

$$\left.\begin{aligned} t_E2 &= t_S2 + k_T/r \\ &= t_S2 + \frac{\ell N + n(1 - N)}{r} \end{aligned}\right\}. \tag{B-72}$$

Clearly, the TDMA message ending time is minimized by choosing $n = \ell$, so that

$$t_E2\Big|_{n = \ell} = t_S2 + \ell/r. \tag{B-73}$$

The additional system waiting time for the TDMA system over the FDMA system, ΔW, is therefore given by

$$\left.\begin{aligned} \Delta W = t_E2\Big|_{n = \ell} - t_E1 &= t_S2 + \ell/r - t_S1 - N\ell/r \\ &= t_S2 - t_S1 - (N - 1)\ell/r = \Delta t - (N - 1)\ell/r, \end{aligned}\right\} \tag{B-74}$$

where $\Delta t = t_S2 - t_S1$.

To find the mean waiting time for TDMA, we can find the expected value of ΔW and add this to the mean waiting time for the FDMA system, as given by equation B-69. The only random variable in the equation for ΔW is Δt, so we must find the expected value of Δt. The message may arrive at any point in a frame. If the message arrives at the beginning of a frame ($t = 0 + \epsilon$)*, then the TDMA system must wait a whole frame (a time of Nn/r) before transmission can start, or

$$\Delta t_{max} = Nn/r. \tag{B-75}$$

If the message arrives at the very end of a frame ($t = Nn/r - \epsilon$)*, then the TDMA system can start transmission immediately, or

$$\Delta t_{min} = 0. \tag{B-76}$$

The message arrivals are random and therefore not synchronized with the frame. It follows that Δt is uniformly distributed from 0 to Nn/r so that the mean Δt is

$$\overline{\Delta t} = Nn/2r. \tag{B-77}$$

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* ϵ is an infinitesimal.

From equations B-74 and B-77 setting n equal to its optimum value, ℓ, we obtain

$$\Delta\overline{W} = \frac{N\ell}{2r} - \frac{(N-1)\ell}{r}, \text{ or} \tag{B-78}$$

$$\Delta\overline{W} = \frac{\ell}{r}\left(\frac{2-N}{2}\right). \tag{B-79}$$

The total TDMA system waiting time, W, is obtained by adding equation B-79 to equation B-69 to obtain

$$\begin{aligned} W &= \frac{\ell}{r}\frac{N}{2}\left[\frac{2 - N\rho'}{1 - N\rho'}\right] + \frac{\ell}{r}\left[\frac{2-N}{2}\right] \\ &= \frac{\ell}{r}\left[\frac{N/2}{1 - N\rho'} + 1\right]. \end{aligned} \tag{B-80}$$

This result was obtained by assuming that there is no queue. Consideration of figure B-31 reveals, however, that if there is a queue in the FDMA system, the ΔW will be the same for each sequence of messages in the TDMA system until the FDMA queue is emptied. Equation B-80 is therefore an exact solution for the TDMA with M/D type traffic.

B.5.2.3 Slotted ALOHA

An analysis of a slotted ALOHA type assignment system is given by Kleinrock (reference 2). When two data packets collide they must be retransmitted later with some random delay so that they will not collide again. If the retransmission delay after detection of a collision is uniformly distributed over K packet lengths, then the mean system waiting time is very nearly minimized over the range of throughput which is of interest by choosing $K = 15$. The mean packet delay measured in packet lengths, D, is given by Kleinrock (reference 2) as

$$D = D_p + 1 + \frac{1-q}{q_t}\left[D_p + 1 + \frac{K-1}{2}\right], \tag{B-81}$$

where D_p is the round trip propagation delay measured in packet lengths and where q and q_t are nonlinear parametric functions of K, q, q_t, S, and G, where S is the channel utilization factor and G is the average number of packet transmissions attempted per slot. Since these nonlinear equations cannot be solved analytically, the value of D was approximated by an empirically derived formula for $K = 15$. The empirical formula is

$$D = \begin{cases} D_p + 1 + 4\,(D_p + 8)\,(S)^{3/2} & \text{for } S < 0.35 \\ \infty & \text{for } S > 0.35. \end{cases} \tag{B-82}$$

Equation B-82 is plotted in figure B-32 along with points from Kleinrock (reference 2) for $K = 15$ and $D_p = 12$. Rewriting equation B-82 in terms of the symbols already introduced gives

$$W = \begin{cases} \frac{\ell}{r}\left\{D_p + 1 + 4(D_p + 8)\,(N\rho')^{3/2}\right\} & \text{for } N\rho' < 0.35 \\ \infty & \text{for } N\rho' > 0.35. \end{cases} \tag{B-83}$$

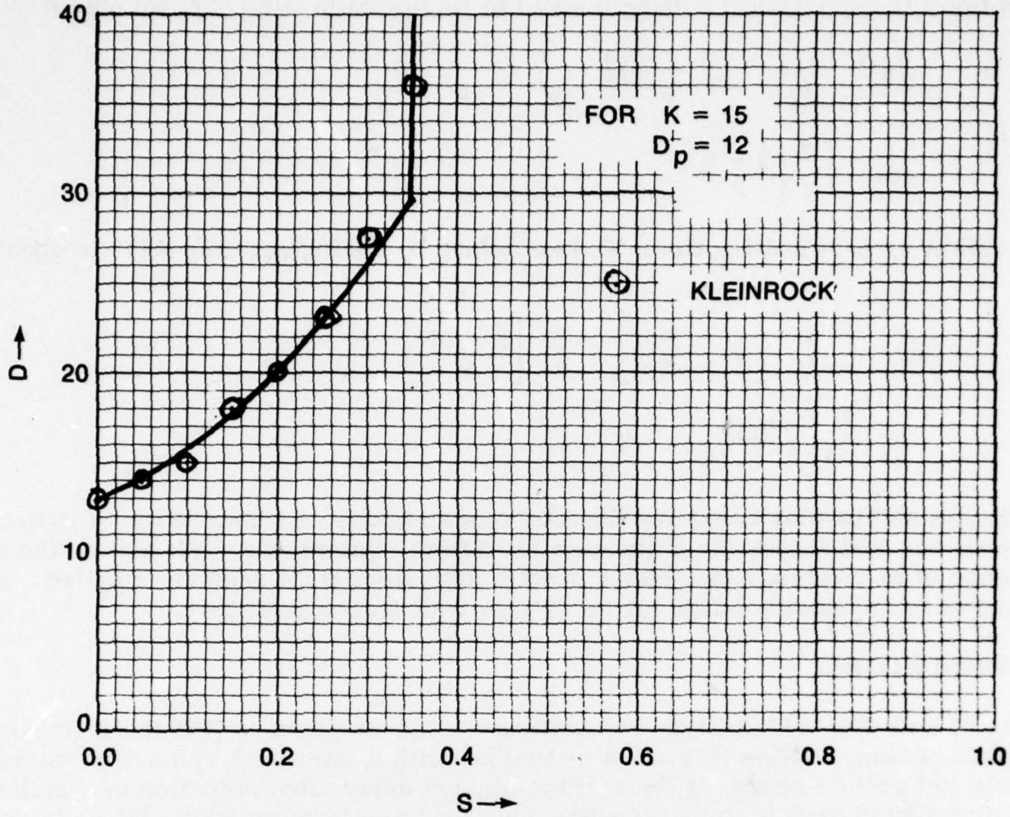

Figure B-32. System Waiting Time for Slotted ALOHA System.

B.5.3 Random Length Messages With Random Arrivals

In paragraph B.5.3 we will derive the equations for the mean system waiting time, W, for those cases where the messages have random length and random arrival times. The message arrival statistics for messages with random arrivals is treated in paragraph B.5.2, and the statistics a[illegible] described by equations B-60, B-61 and B-62.

For random message lengths, we shall assume an exponential distribution of message length, x, given by

$$f(x) = \begin{cases} 0 & \text{for } x < 0 \\ (1/\bar{x})e^{-x/\bar{x}} & \text{for } x \geq 0 \end{cases} \tag{B-84}$$

where $\bar{x}$ is the mean service time in seconds per message. The mean message transmission or service time, $\bar{x}$, is defined in terms of the service rate, μ , by

$$\bar{x} = 1/\mu \, . \tag{B-85}$$

It is assumed that the average message length, $\bar{x}$, is the same for all users.

The waiting time in queue, W_q, is given by equation B-63 for this case also. In order to evaluate W_q, we must know the message arrival rate, λ, the mean service time, $\overline{x}$, and the variance of the service time, σ_b^2. The system time, W, is given by equation B-64.

The assignment systems which we will consider in this section are fixed assignment, using FDMA and TDMA; random assignment, using slotted ALOHA; polled assignment; and reservation assignment, using a TDMA and a slotted ALOHA type orderwire.

B.5.3.1 Fixed Assignment FDMA

For fixed assignment FDMA systems, we assume that the total channel bit rate capacity of r bits per second is divided into N channels, each with a bit rate of r', given in equation B-66, and that each of the N users occupies a single FDMA channel.

The mean waiting time, W, for a single FDMA channel is obtained from equations B-63 and B-64 as

$$W = \overline{x} + \frac{(\lambda'\overline{x})\,\overline{x}\,[1 + \sigma_b^2/\overline{x}^2]}{2\,[1 - (\lambda'\overline{x})]}, \qquad \text{(B-86)}$$

where λ' is the mean message arrival rate for a single FDMA channel.

The mean message duration, $\overline{x}$, is given by

$$\overline{x} = \overline{\ell}/r' = N\overline{\ell}/r. \qquad \text{(B-87)}$$

The variance of the message duration, σ_b^2, for an exponentially distributed message length is

$$\sigma_b^2 = \overline{x}^2 = N^2(\overline{\ell}/r)^2. \qquad \text{(B-88)}$$

Substituting equations B-87 and B-88 into B-86 and simplifying gives

$$W = \frac{\overline{\ell}}{r}\,\frac{N}{1 - \lambda' N\overline{\ell}/r}. \qquad \text{(B-89)}$$

Substituting

$$\rho' = \lambda'\overline{\ell}/r \qquad \text{(B-90)}$$

into equation B-89 gives

$$W = \frac{\overline{\ell}}{r}\,\frac{N}{1 - N\rho'}. \qquad \text{(B-91)}$$

B.5.3.2 Fixed Assignment TDMA

In a fixed assignment TDMA system, the message is divided into fixed length time slots before being transmitted. The message statistics are thus altered. This is known as synchronous TDMA in computer systems terminology. In analyzing the TDMA system it is convenient to separate the analysis into two steps. In the first step, the message is divided into fixed length packets. The system waiting time is then calculated as if this message were transmitted on an FDMA channel. In the second step, the increase or decrease in the waiting time in going from an FDMA channel to a burst TDMA channel is calculated. This gives an exact solution for the TDMA system.

B.5.3.2.1 Length Statistics of Blocked Messages

When messages with exponentially distributed message lengths are divided into fixed length blocks, the statistics of the message are changed since the message now must be an integral number of blocks long. The blocked message has a different mean length and variance than the unblocked message. Since the original message length distribution is exponential, the probability, q, that the message will not end in any given block, given that it has not ended prior to that block, is

$$q = e^{-b/\overline{\ell}}. \tag{B-92}$$

Here b is the number of bits in a block and $\overline{\ell}$ is the mean number of bits in the message. Therefore, the probability, P_k, that the message will be exactly k blocks long is

$$P_k = q^{k-1}(1 - q). \tag{B-93}$$

The mean message length, $\overline{m}$, measured in blocks is given by

$$\begin{aligned} \overline{m} &= \sum_{k=1}^{\infty} kP_k = \sum_{k=1}^{\infty} kq^{k-1} (1 - q) \\ &= \sum_{k=1}^{\infty} kq^{k-1} - q \sum_{k=1}^{\infty} kq^{k-1} \\ &= (1 - q) \sum_{k=1}^{\infty} kq^{k-1}. \end{aligned} \tag{B-94}$$

This infinite sum in the last expression is a well known series expansion of $1/(1 - q)^2$. Thus the mean blocked message length becomes

$$\overline{m} = \frac{1 - q}{(1 - q)^2} = 1/(1 - q). \tag{B-95}$$

The mean square message length, $\overline{m^2}$, is given by

$$\begin{aligned} \overline{m^2} &= \sum_{k=1}^{\infty} k^2 P_k = \sum_{k=1}^{\infty} k^2 q^{k-1} (1 - q) \\ &= \frac{1 - q}{q} \sum_{k=0}^{\infty} k^2 q^k. \end{aligned} \tag{B-96}$$

This infinite series can be readily evaluated using z transforms by letting $f(k) = k^2$ with the result that

$$\overline{m^2} = \frac{1-q}{q} \times \frac{1/q + 1}{q(1/q - 1)^3} = \frac{1+q}{(1-q)^2}. \tag{B-97}$$

Therefore, the variance in the blocked message length, σ_m^2, measured in b's is

$$\sigma_m^2 = \overline{m^2} - (\overline{m})^2 = \frac{q}{(1-q)^2}. \tag{B-98}$$

In most TDMA systems, a block consists of a preamble of "a" bits follwed by "b" information bits. The mean duration of a blocked message with a preamble, therefore, is

$$\overline{x} = \overline{m}(a + b)/r' = \overline{m}(a/\overline{\ell} + b/\overline{\ell})\, N\overline{\ell}/r, \tag{B-99}$$

and the variance of the message duration is

$$\sigma_b^2 = \sigma_m^2 (b/r')^2$$

$$= \frac{q}{(1-q)^2} \frac{b^2}{(r')^2} \tag{B-100}$$

$$= q\overline{m}^2 \left(\frac{b}{\overline{\ell}}\right)^2 \left(\frac{\overline{\ell}}{r}\right)^2 N^2.$$

B.5.3.2.2 System Waiting Time for Block Messages

The system waiting time, W*, for a message which has been divided into fixed length blocks and transmitted at a bit rate of 1/Nth of the channel capacity can be obtained by substituting equations B-99 and B-100 into equation B-86 and simplifying to obtain

$$W^* = \left(\frac{\overline{\ell}}{r}\right)\frac{1}{2}\, \alpha\overline{m}N \left\{\frac{2 - \alpha\overline{m}N\lambda'(\overline{\ell}/r)\left[1 - q(b/\overline{\ell}/\alpha)^2\right]}{1 - \alpha\overline{m}N\lambda'(\overline{\ell}/r)}\right\} \tag{B-101}$$

where

$$\alpha = a/\overline{\ell} + b/\overline{\ell}.$$

B.5.3.2.3 System Waiting Time

The mean system waiting time for TDMA, W, is the mean system waiting time for the equivalent blocked FDMA system, W*, plus the additional delay due to transmitting the blocks in TDMA bursts, $\Delta\overline{W}$. This additional delay can be derived by reference to figure B-33. Here is is assumed that a block of a message from a user arrives at time t_s. For the equivalent FDMA block, the block transmission starts immediately. The block consists of an "a" bit preamble plus "b" information bits and is transmitted at a bit rate, r', which is 1/Nth of the channel capacity. The transmission of the block will be completed at time t_e given by

$$t_e = t_s + (a + b)/r' = t_s + (a + b)N/r. \tag{B-102}$$

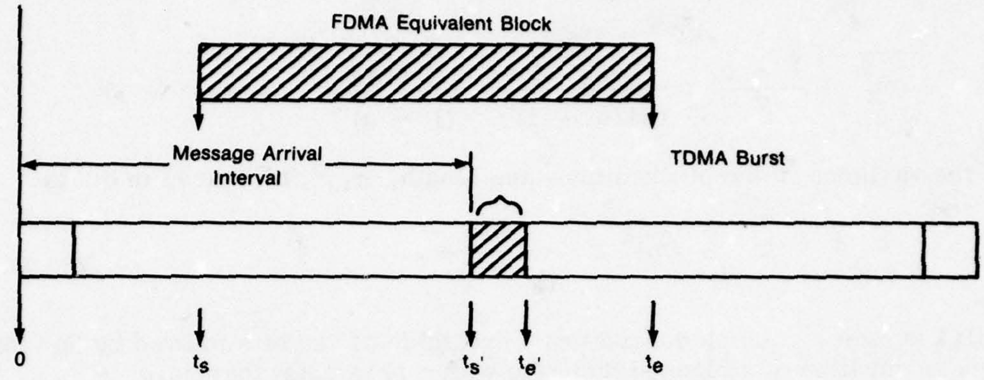

Figure B-33. Relationship Between TDMA Burst and FDMA Equivalent Block.

The transmission of the corresponding TDMA burst will start at the beginning of the user's first time slot after the block arrival. As diagrammed in figure B-33, this is one frame after t = 0 and is indicated by t_s', which is given by

$$t_s' = N(a + b)r. \tag{B-103}$$

The transmission of this block will be completed at the end of this burst at a time t_e' given by

$$t_e' = (N + 1)(a + b)/r. \tag{B-104}$$

The increase in system delay of the TDMA system over the equivalent blocked FDMA system, ΔW, is given by

$$\begin{aligned} \Delta W &= t_e' - t_e \\ &= (N + 1)(a + b)/r - t_s - (a + b)N/r \\ &= (a + b)/r - t_s. \end{aligned} \tag{B-105}$$

Since the message arrivals are independent of the time slots, t_s will be uniformly distributed over exactly one frame. The expected value of t_s, $E[t_s]$, is therefore 1/2 the frame duration. Therefore, the mean additional system waiting time, $\overline{\Delta W}$, is given by

$$\begin{aligned} \overline{\Delta W} &= (a + b)/r - E[t_s] \\ &= (a + b)/r - 1/2N(a + b)/r \\ &= -1/2 \frac{(a + b)}{r} [N - 2] \\ &= -1/2 (a/\bar{\ell} + b/\bar{\ell})(\bar{\ell}/r)(N - 2) \\ &= -\frac{\alpha}{2} (\bar{\ell}/r)(N - 2). \end{aligned} \tag{B-106}$$

Note that this is the expected additional delay of any message block. This is the expected additional delay for any and all bursts. It follows that this is the additional delay for the message, regardless of whether the message is a new arrival or has waited in queue.

The total mean system waiting for TDMA is given by

$$W = W^* + \overline{\Delta W}$$

$$= (\bar{\ell}/r)\,(\alpha/2)\left\{\bar{m}N\left[\frac{2 - \alpha\bar{m}N\rho'\left[1 - (1 - 1/\bar{m})\,(b/\bar{\ell}/\alpha)^2\right]}{1 - \alpha\bar{m}N\rho'}\right] - (N - 2)\right\} \quad \text{(B-107)}$$

where $\bar{m}$, α , and ρ' are given by

$$\left.\begin{aligned} \bar{m} &= 1/(1 - e^{-b/\bar{\ell}}) \\ \alpha &= a/\bar{\ell} + b/\bar{\ell} \\ \rho' &= \lambda'(\bar{\ell}/r). \end{aligned}\right\} \quad \text{(B-108)}$$

B.5.3.2.4 Optimum Block Size

The system waiting time, W, is a function of the block length chosen. If a very long block length or burst is used, then the messages will generally be longer than the block, and most of the transmission time will be wasted in transmitting blanks or null characters. On the other hand, if the block is too short, most of the time is wasted in transmitting the block preamble. There is thus an optimum block length. The normalized system waiting time, $W/(\bar{\ell}/r)$, vs normalized block length, $b/\bar{\ell}$, is plotted for various values of $a/\bar{\ell}$ and ρ in figures B-34 through B-36. It will be noted that the minimum waiting time is relatively independent of the utilization factor, ρ. The minimum waiting time is obtained approximately by setting $b/\bar{\ell}$ to the value given by (reference 4):

$$b/\bar{\ell}\Big|_{\text{optimum}} = \sqrt{2a/\bar{\ell}}\,. \quad \text{(B-109)}$$

B.5.3.3 Polled Assignment

In polled assignment, a fixed number of users share the channel capacity sequentially, as with TDMA, except that instead of using a fixed length time slot, a user continues to use the channel after it has been obtained and until all stored traffic has been forwarded. The users access the channel in sequence, but the time slot and frame duration are random variables. This is known as asynchronous TDMA in computer systems terminology. In polled assignment, there is no need for a preamble before every message, but guard time and a preamble are required between user accesses. Such systems have been analyzed by Chu and Konheim (reference 5). The queue waiting time measured in bits, D_m, is given (reference 5) as

$$D_m = \frac{1}{2}\frac{N\sigma^2}{1 - N\mu} + \frac{1}{2}\frac{Nd(1 - \mu)}{1 - N\mu} + \frac{1}{2}(1 - \mu), \quad \text{(B-110)}$$

where N is the number of users or terminals; d is the space in bits between users for delay, guard, and preamble; and μ and σ^2 are the mean and the variance, respectively, of the

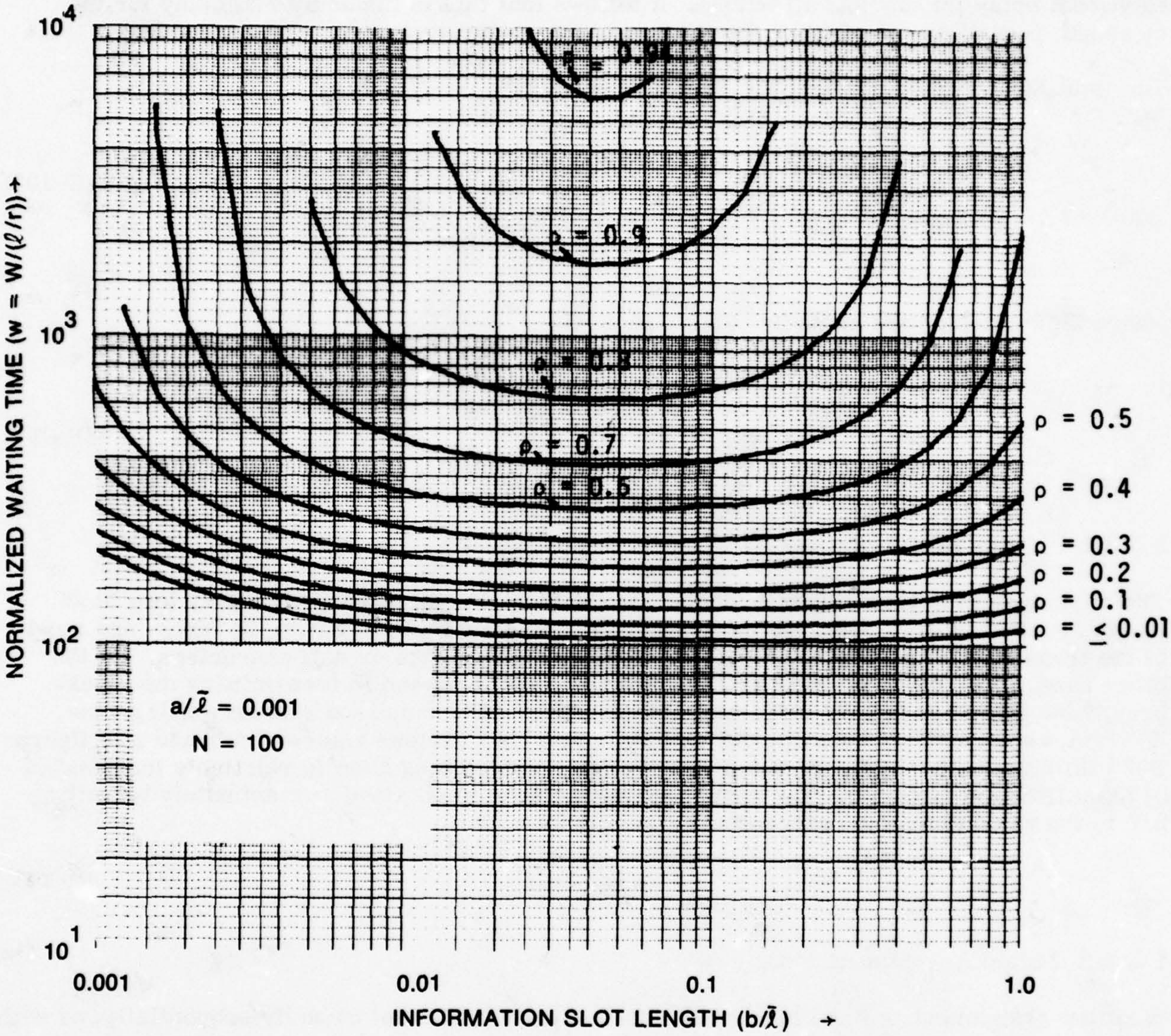

Figure B-34. System Waiting Time Versus Slot Length for TDMA With $a/\bar{\ell} = 0.001$ for Various Utilization Factors (ρ).

number of message bit arrivals from a single user during a one-bit transmission period (z). It is shown (reference 5) that

$$\mu = E\left[z\right] = \frac{\lambda^*}{1 - q} \tag{B-111}$$

$$\sigma^2 = E\left[(z - \mu)^2\right] = \frac{\lambda^*(1 + q)}{(1 - q)^2}, \tag{B-112}$$

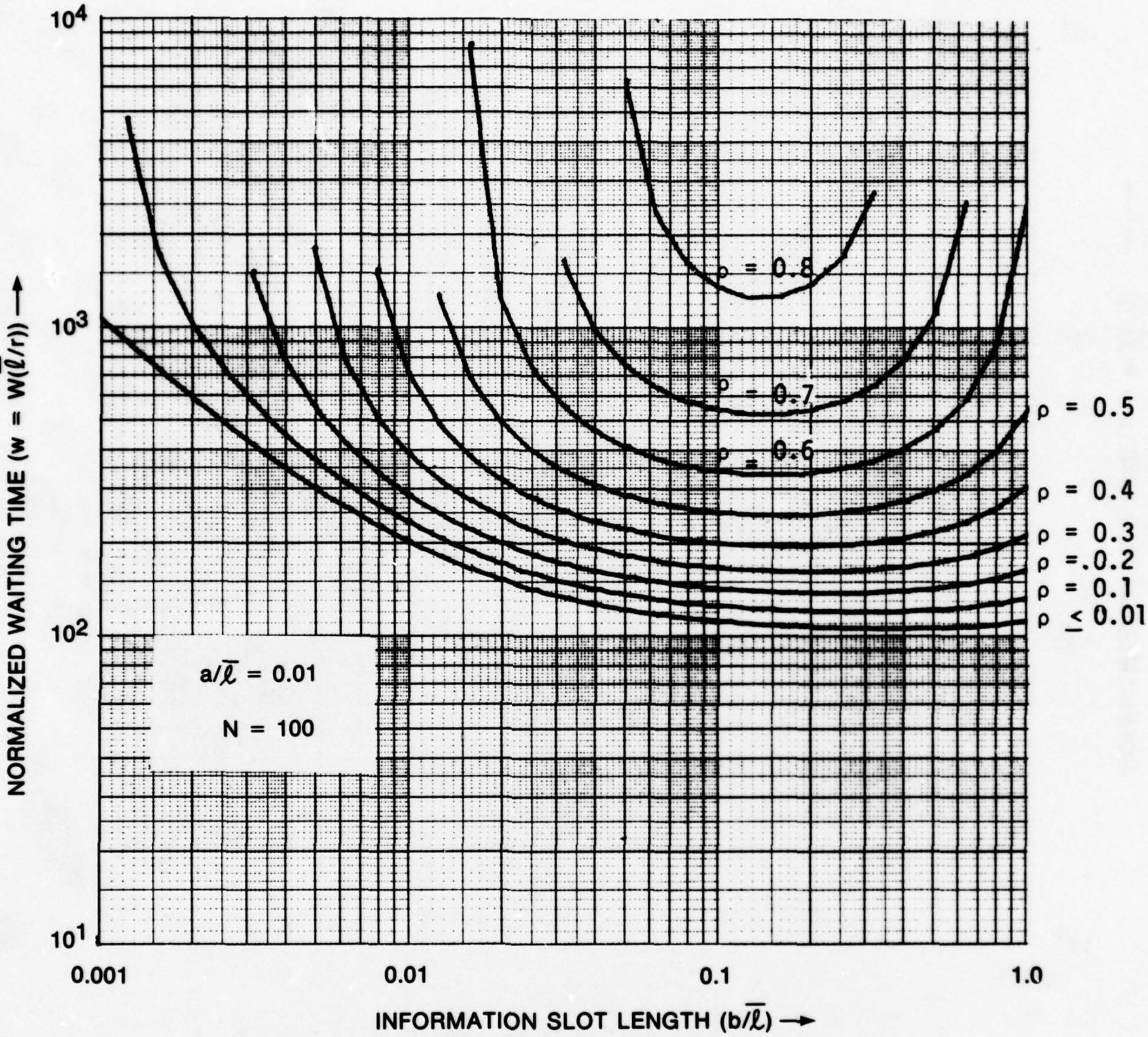

Figure B-35. System Waiting Time Versus Slot Length for TDMA With $a/\bar{\ell} = 0.01$ for Various Utilization Factors (ρ).

where q is related to the mean number of bits in a message, $\bar{\ell}$, by

$$\bar{\ell} = \frac{1}{1 - q}, \tag{B-113}$$

and λ^* is related to the single user message arrival rate, λ', by

$$\lambda^* = 1 - e^{-\lambda'/r} = \lambda'/r. \tag{B-114}$$

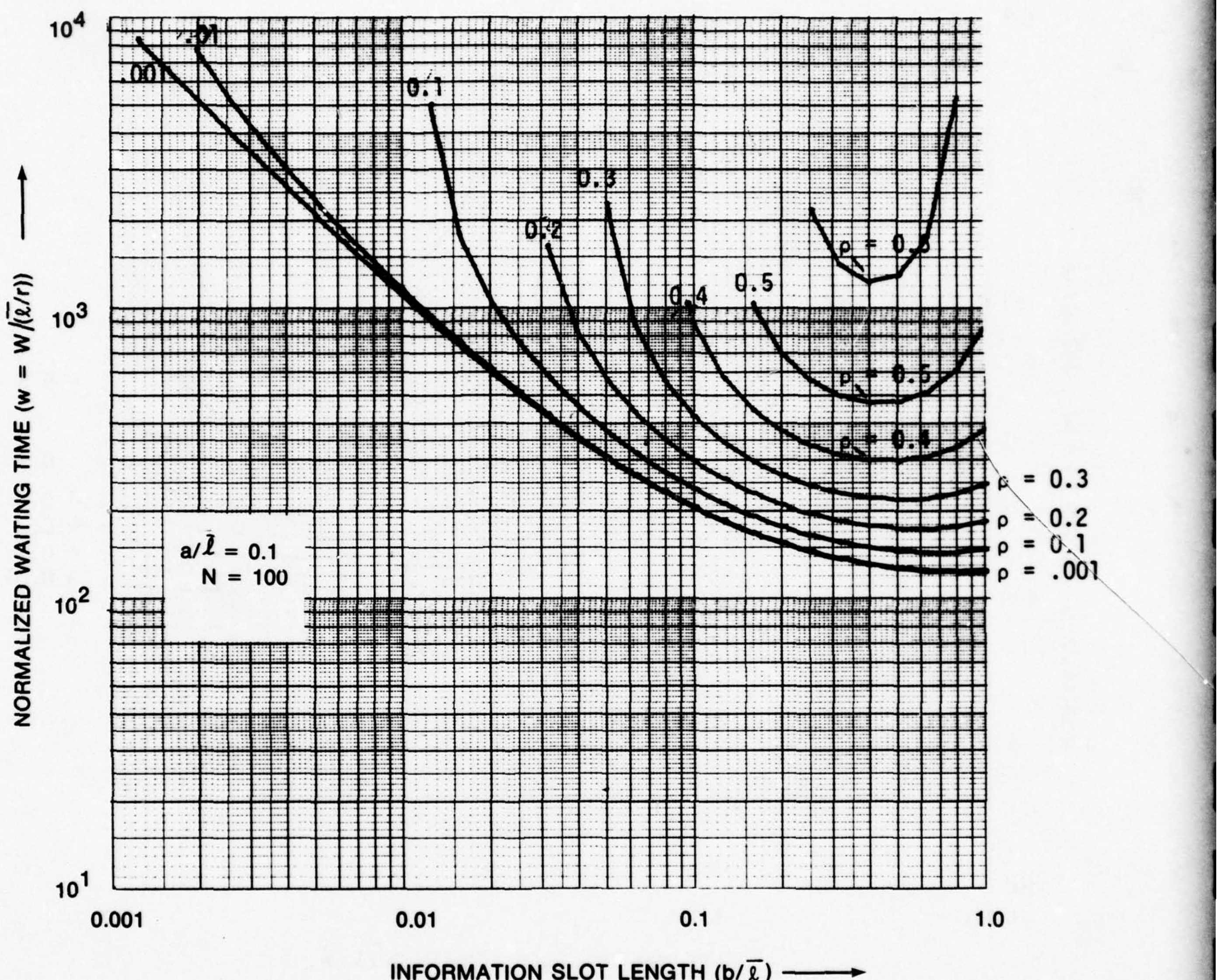

Figure B-36. System Waiting Time Versus Slot Length for TDMA With $a/\bar{\ell} = 0.1$ for Various Utilization Factors (ρ).

Substituting equations B-113 and B-114 into equations B-111 and B-112 gives

$$\mu = \lambda^* \bar{\ell} = \lambda'(\bar{\ell}/r) = \rho' \qquad \text{(B-115)}$$

and

$$\sigma^2 = \lambda^* \bar{\ell}^2 (2 - 1/\bar{\ell}) = 2\lambda'(\bar{\ell}/r)\bar{\ell} = 2\rho'\bar{\ell}, \qquad \text{(B-116)}$$

where ρ' is given by equation B-108.

The total mean system waiting time, W, is the queue waiting time plus the transmission time, or

$$W = D_m/r + \bar{\ell}/r. \tag{B-117}$$

Combining equations B-110, B-115, B-116, and B-117 gives

$$W = \frac{\bar{\ell}}{r}\left\{\frac{N\rho'}{1 - N\rho'} + \frac{1}{2}(d/\bar{\ell})\frac{N(1 - \rho')}{1 - N\rho'} + \frac{1}{2\bar{\ell}}(1 - \rho') + 1\right\}. \tag{B-118}$$

The next to the last term is normally much smaller than the rest and can therefore be neglected, resulting in

$$W \approx \frac{\bar{\ell}}{r}\left\{1 + \frac{N\rho'}{1 - N\rho'} + \frac{d/\bar{\ell}}{2}\,\frac{N(1 - \rho')}{1 - N\rho'}\right\}. \tag{B-119}$$

B.5.3.4 Slotted ALOHA

Slotted ALOHA has been analyzed for fixed length messages with random arrivals in paragraph B.5.2.3. In the case of random length messages, the total message length of ℓ bits is divided into packets of b information bits each. Each packet is transmitted and retransmitted after a random waiting period until it arrives at the satellite without colliding with a packet from another terminal. This is determined by monitoring the satellite broadcast. Once the first packet has been successfully transmitted, the next packet is transmitted immediately. We can approximate the waiting time by using the results from paragraph B.5.2.3 with an increased amount of traffic to allow for the fact that there are multiple packets per message.

The mean number of packets, $\bar{m}$, of length b bits in a message with a mean length of $\bar{\ell}$ bits was derived in paragraph B.5.3.2.1 and is given by

$$\bar{m} = \frac{1}{1 - e^{-b/\bar{\ell}}}. \tag{B-120}$$

For a single packet of the message, the mean system waiting time, W_1, is obtained from equation B-83 by increasing the rate of message arrivals by a factor of $\bar{m}$ to obtain

$$W_1 = \begin{cases} \dfrac{(a + b)}{r}\left\{D_p + 1 + 4(D_p + 8)\left[\dfrac{N\bar{m}\lambda'(a + b)}{r}\right]^{3/2}\right\} & \text{for } N\bar{m}\rho' \le 0.35 \\ \infty & \text{for } N\bar{m}\rho' > 0.35 \end{cases} \tag{B-121}$$

The total mean system waiting time, W, is $\bar{m}$ times the mean waiting time for one packet. Multiplying equation B-121 by $\bar{m}$ and performing additional manipulation gives

$$W = \frac{\bar{\ell}}{r}\bar{m}(a/\bar{\ell} + b/\bar{\ell})\left\{D_p + 1 + 4(D_p + 8)\bar{m}^{3/2}(a/\bar{\ell} + b/\bar{\ell})^{3/2}(N\rho')^{3/2}\right\}. \tag{B-122}$$

The optimum number of information bits in a block is given approximately by (reference 4):

$$b/\bar{\ell} = \sqrt{2a/\bar{\ell}}. \tag{B-123}$$

B.5.3.5 Reservation Assignment

In a reservation assignment system, a user requiring service requests a channel. This request in effect enters a reservation for the message in a common virtual queue. The position in queue which the message is given depends on the queuing protocol used. This could be a first-come, first-served system or a priority system. When all messages which are ahead in the queue have been served, the subject message is transmitted. The entire available channel capacity is devoted to this message once it comes to the head of the queue.

If we neglect the channel capacity and waiting time required for the orderwire, this becomes the classical M/G/1 system (reference 1). The mean system waiting time is given by equation B-64.

Assuming a mean message length of $\bar{\ell}$ information bits preceded by an a_1-bit preamble, the mean and variance of the message length are given by

$$\bar{x} = (a_1 + \bar{\ell})/r \tag{B-124}$$

$$\sigma_b^{\,2} = (\bar{\ell}/r)^2, \tag{B-125}$$

so that the M/G/1 mean waiting time becomes

$$W = (\bar{\ell}/r)\,(\alpha/2)\left(\frac{2 - \alpha N\rho'(1 - 1/\alpha^2)}{1 - \alpha N\rho'}\right), \tag{B-126}$$

where α is defined as

$$\alpha = 1 + a_1/\bar{\ell}\ . \tag{B-127}$$

B.5.3.5.1 Orderwire Considerations

Let the total bit rate, r, be divided into r_1 bits/second for the message channel and r_2 bits/second for the orderwire channel, where

$$r = r_1 + r_2. \tag{B-128}$$

Let that fraction of the total bit rate capacity devoted to the orderwire be θ , so that

$$\left.\begin{aligned} r_2 &= \theta r \\ r_1 &= (1 - \theta)r \end{aligned}\right\} \tag{B-129}$$

The total system waiting time, W, is the sum of the waiting time to get the message entered in the virtual queue, W_2, plus the system waiting time in the message channel, W_1, or

$$W = W_1 + W_2. \tag{B-130}$$

The separation of the total channel capacity into orderwire and message subchannels can be accomplished by either FDMA or TDMA. We shall assume here that no loss in channel capacity results from this division and that the division is accomplished using FDMA. The results using TDMA would be similar.

B.5.3.5.2 Reservation Assignment With TDMA Orderwire

For a TDMA orderwire, the orderwire mean system waiting time is obtained from equation B-80 with $\ell = a_2$, the orderwire message length, and with $r = r_2$. The mean message waiting time for the message is obtained from equation B-126, with $r = r_1$. The total mean system waiting time is then given by equation B-130. Using equations B-128 and B-129 gives

$$W = \frac{\bar{\ell}}{r(1-\theta)}(\alpha/2)\left\{\frac{2-[\alpha N\rho'/(1-\theta)]\,[1-1/\alpha^2]}{1-\alpha N\rho'/(1-\theta)}\right\} + \frac{a_2}{r\theta}\left\{\frac{N/2}{1-N\lambda' a_2/(r\theta)}+1\right\}. \quad \text{(B-131)}$$

Manipulating equation B-131 with the substitution

$$\gamma = a_2/\bar{\ell}, \quad \text{(B-132)}$$

we obtain

$$W = \frac{\bar{\ell}}{r}\left\{\frac{\alpha}{2(1-\theta)}\left[\frac{2-\alpha N\rho'(1-1/\alpha^2)/(1-\theta)}{1-\alpha N\rho'/(1-\theta)}\right] + \frac{\gamma}{2\theta}\left[\frac{N}{1-\gamma N\rho'/\theta}+2\right]\right\}. \quad \text{(B-133)}$$

The system waiting time, W, is affected by the division of the total channel capacity between the message channel and the orderwire channel as shown in figures B-37 and B-38.

The optimum value of θ is a function of the utilization factor, ρ; the number of terminals in the system, N; and the length of the preambles and reservation message, ($a_1/\bar{\ell}$ and $a_2/\bar{\ell}$). *Over the range of our interest* ($3 \le N \le 1000$, $.01 \le a_1/\bar{\ell} \le 0.03$, $.01 \le a_2/\bar{\ell} \le 0.03$), the value of θ, which minimizes waiting time, is given approximately by the emperical equation:

$$\theta\Big|_{\text{optimum}} = a_2/\bar{\ell} + 0.227\log_{10}N(1 - a_1/\bar{\ell} - a_2/\bar{\ell} - \rho). \quad \text{(B-134)}$$

B.5.3.5.3 Reservation Assignment With Slotted ALOHA Orderwire

The mean system waiting time, W, for a reservation assignment system with a slotted ALOHA orderwire can be obtained from equation 5-83 in conjunction with equations B-126 and B-83. The result is

$$W = \frac{\bar{\ell}}{r_1}\;\frac{\alpha}{2}\left[\frac{2-(1-1/\alpha^2)\alpha N\lambda'(\bar{\ell}/r_1)}{1-\alpha N\lambda'(\bar{\ell}/r_1)}\right] + \frac{a_2}{r_2}\left[1+32(N\lambda' a_2/r_2)^{3/2}\right]\Bigg\} \quad \text{(B-135)}$$

for $N\lambda' a_2/r_2 < 0.35$.

Substituting equations B-129 and B-132 into the above gives

$$W = \left(\frac{\bar{\ell}}{r}\right)\left\{\frac{\alpha}{2(1-\theta)}\left[\frac{2-(1-1/\alpha^2)N\rho'\alpha/(1-\theta)}{1-N\rho'\alpha/(1-\theta)}\right] + \frac{\gamma}{\theta}\left[1+32(N\rho'\gamma/\theta)^{3/2}\right]\right\} \quad \text{(B-136)}$$

for $N\rho'\gamma/\theta < 0.35$.

The system waiting time depends on the channel capacity division between the information and orderwire function as shown in figures B-39 and B-40.

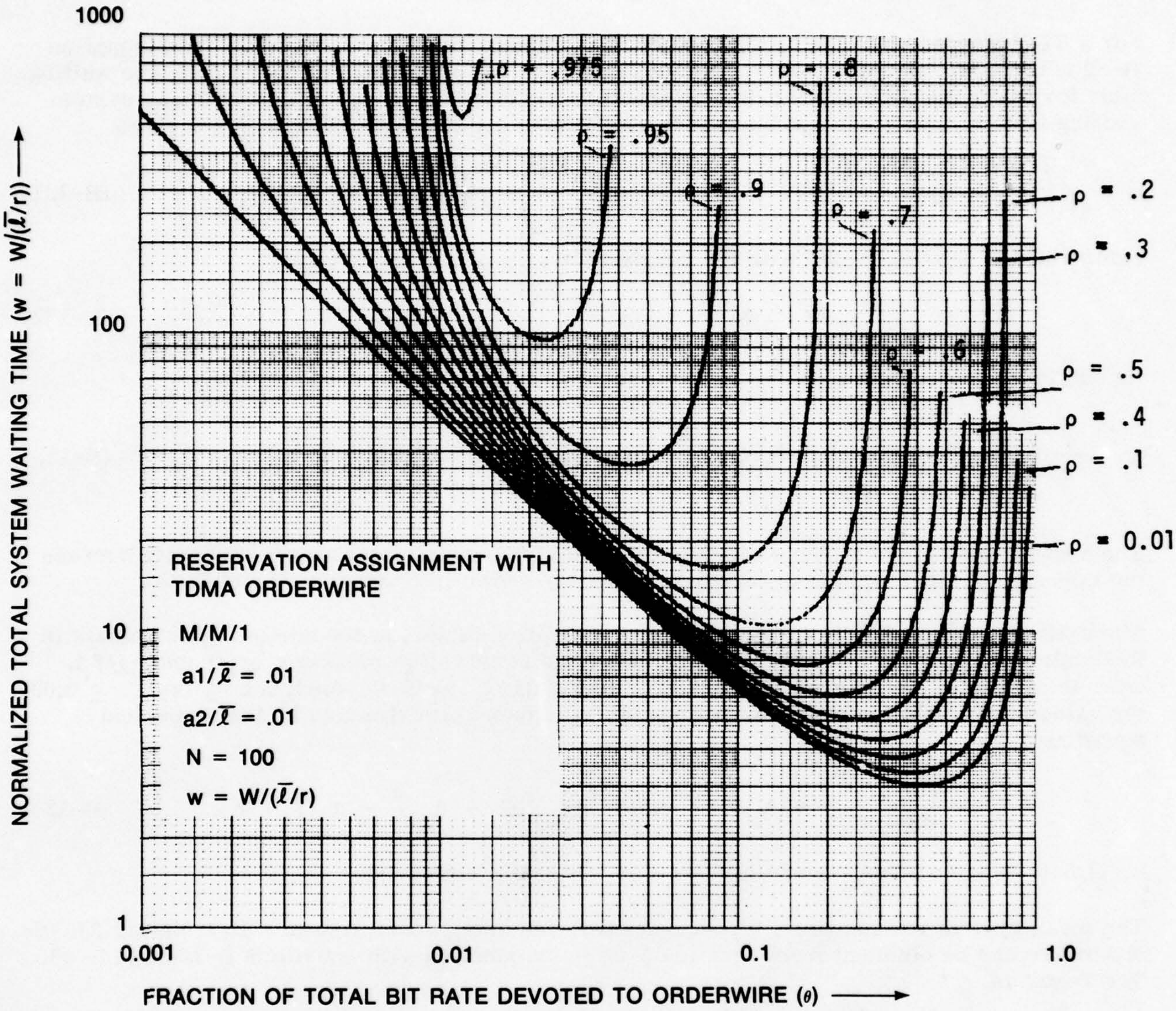

Figure B-37. System Waiting Time (w) for Random Length Messages With Random Arrivals for Reservation Assignment With TDMA Orderwire and 100 Terminals (Equation B-133).

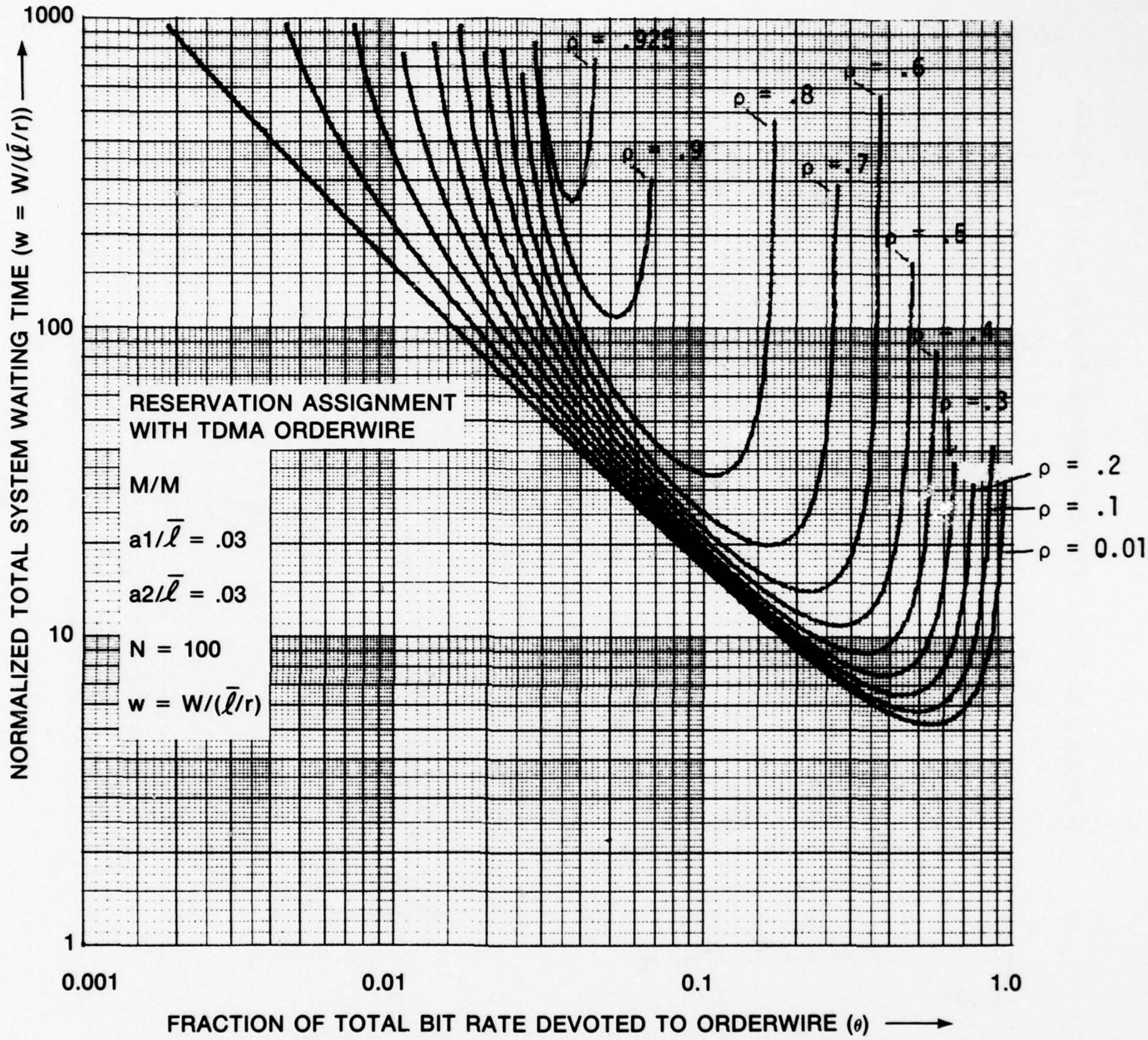

Figure B-38. System Waiting Time (w) for Random Length Messages With Random Arrivals for Reservation Assignment With TDMA Orderwire and 100 Terminals (Equation B-133).

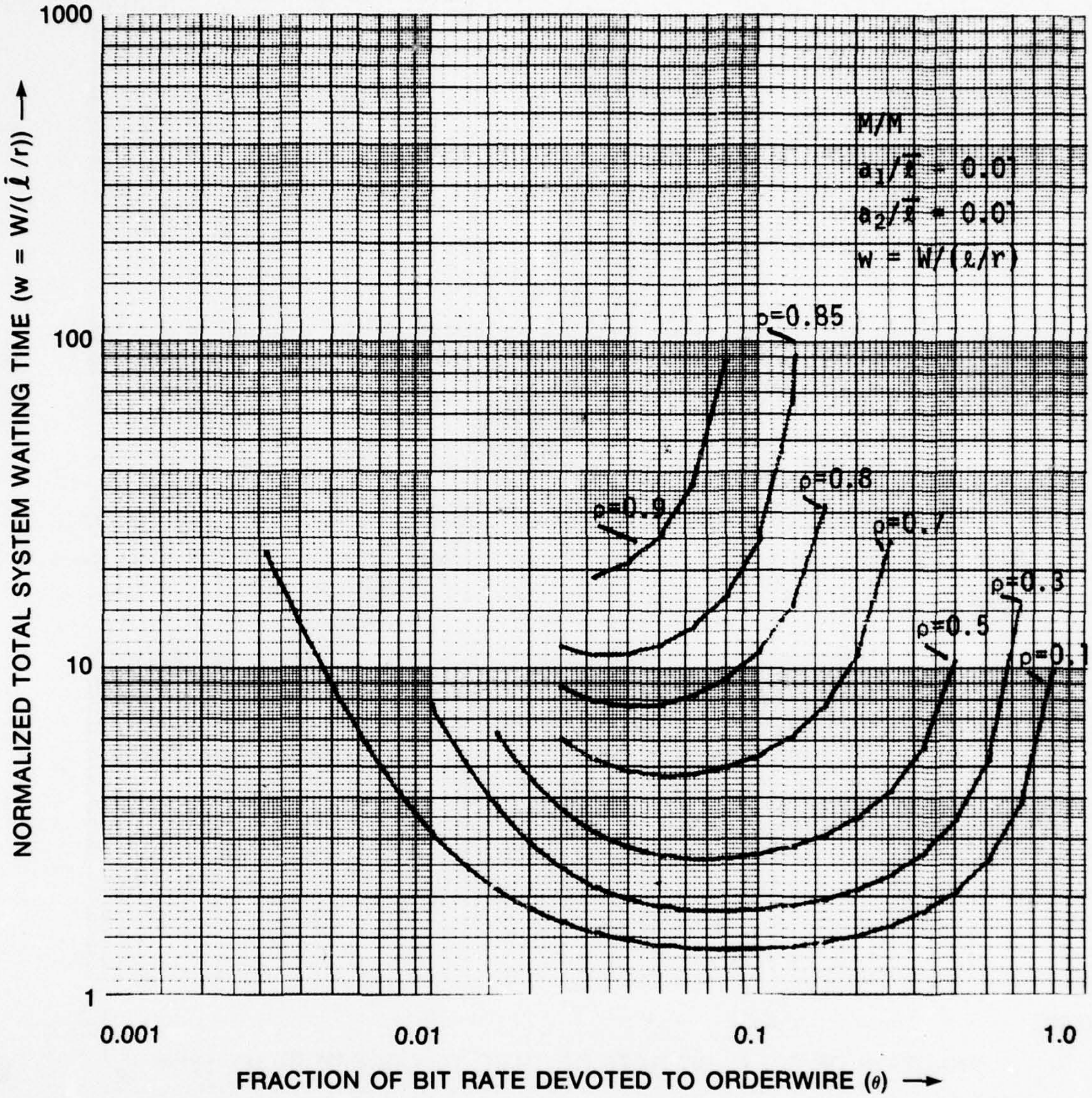

Figure B-39. System Waiting Time (w) for Random Length Messages With Random Arrivals for Reservation Assignment With Slotted ALOHA Orderwire (Equation B-136).

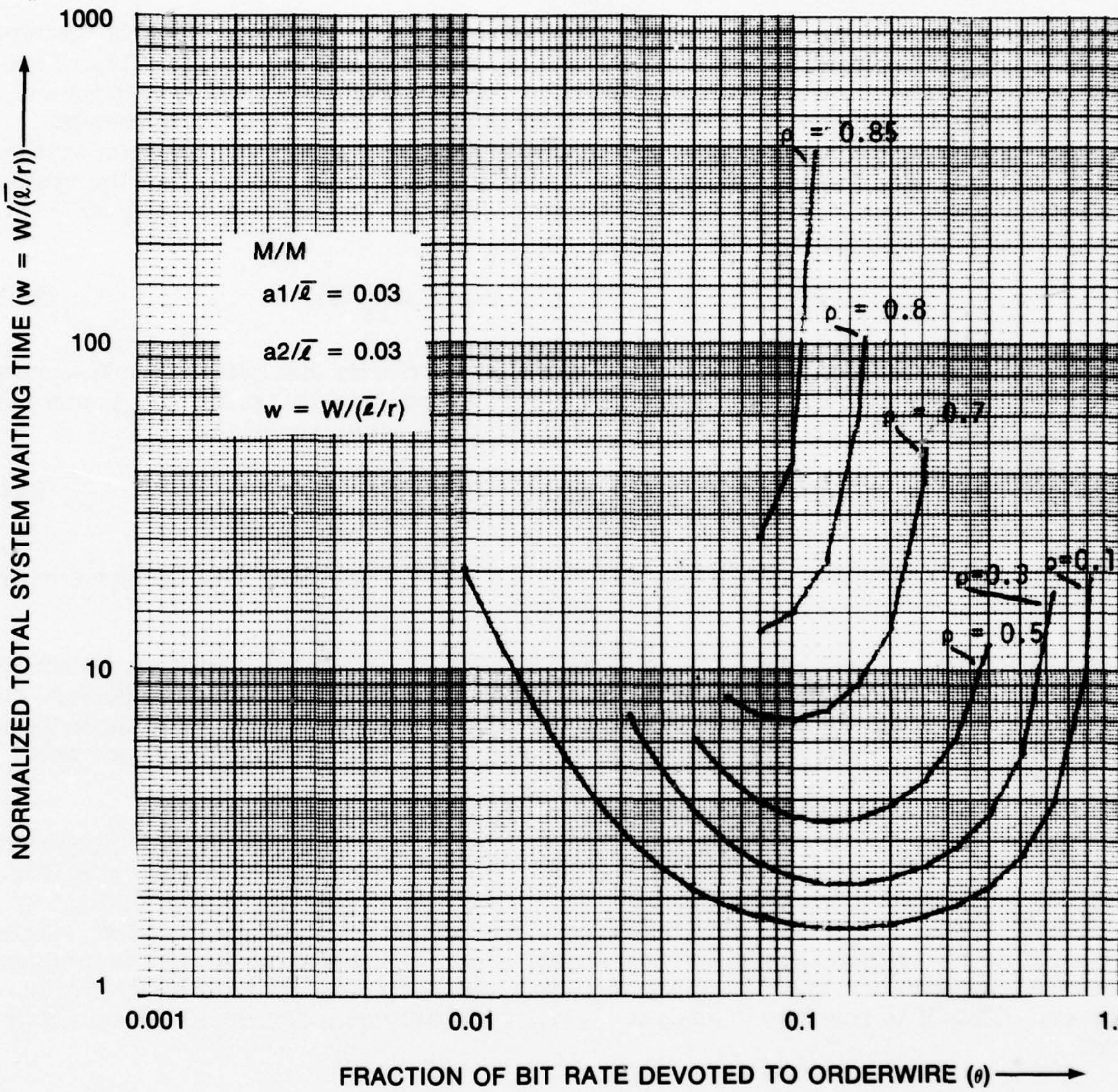

Figure B-40. System Waiting Time (w) for Random Length Messages With Random Arrivals for Reservation Assignment With Slotted ALOHA (Equation B-136).

B.6 EFFECTS OF PRIORITY ON WAITING TIME

It is often desired to design a store-and-forward communication system so that the system waiting time for a message shall not exceed some specified maximum, W_{max}. This is not possible for systems with Poisson distributed arrival times and exponentially distributed message durations since there is no upper limit for system waiting time. It is possible, however, to design a system so that the probability of exceeding a specified system waiting time, W_m, will not exceed some specified upper limit, P_m. The probability that the system waiting time, W, will exceed the specified maximum, W_m, for a single server (M/M/1) first-in, first-out (FIFO) queuing system is given by

$$P_m = P(W > W_m) = \exp(-W_m/\overline{W}), \qquad \text{(B-137)}$$

where $\overline{W}$ is the mean system waiting time. If there is no priority discipline, then W_m must be the desired maximum system waiting time for the highest priority traffic, W_m1; and the mean system waiting time for all traffic, $\overline{W}$, must meet the requirement that

$$\overline{W} \leq -W_m1/\ln(P_m1) \, . \qquad \text{(B-138)}$$

Since W_m1 is often fairly short, this may require that the overall system be designed to provide a very short mean system waiting time, indeed.

In order to allow the use of a smaller communications capacity and still meet the waiting time requirements for all priorities of traffic, a priority queuing discipline must be adopted. In a priority queuing system, higher priority messages are moved ahead of all lower priority messages in the single queue. Within any one priority class, the messages in queue are arranged first-in, first-out.

Assume that the priority-discipline is preemptive or that the time required to complete transmission of a lower priority message when a higher priority message arrives is negligible. With this assumption, the first or highest priority traffic is not interfered with in any way by lower priority traffic so that as far as the highest priority traffic is concerned, the system behaves as if all lower priority traffic were absent. More generally, as far as the n highest priority traffic classes are concerned, the system behaves as if all lower priority traffic were absent. Thus it is possible to analyze a priority system as a sequence of nonpriority systems.

It will be shown that the probability, P_i, that the system waiting time for a priority class i message will exceed a desired maximum, W_{mi}, is given by

$$P_i = \exp(-W_{mi}\,\mu)\exp(W_{mi}\sum_{j=1}^{i-1}\lambda_j)\left[\lambda_i + (\exp(W_{mi}\,\lambda_i) - 1)\sum_{j=1}^{i}\lambda j\right]/\lambda_i \, , \qquad \text{(B-139)}$$

where λ_j is the message arrival rate for priority j messages and μ is the mean message service rate. The mean message service rate is related to the mean message length, $\bar{\ell}$, in bits by

$$\mu = r/\bar{\ell} \; ,$$

where r is the channel bit rate. Solving equation B-139 for the message service rate, μ_i, which will cause the system waiting time for the ith priority class to exceed W_{mi} with a probability P_i, gives

$$\mu_i = \sum_{j=1}^{i-1} \lambda_j + \frac{1}{W_{mi}} \ln \left[\frac{\lambda_i + [\exp(W_{mi}\lambda_i) - 1] \sum_{j=1}^{i} \lambda_j}{\lambda_i P_i} \right]. \qquad \text{(B-140)}$$

The minimum message service rate given by equation B-140 is calculated for each priority class and the system is then designed for the largest resulting service rate, μ_{max}. The required channel bit rate is then

$$r = \mu_{max} \bar{\ell}. \qquad \text{(B-141)}$$

The mean system waiting time, $\overline{W}$, is

$$\overline{W} = \frac{1}{\mu_{max} - \lambda} = \frac{1}{\mu_{max} - \sum_{j=1}^{N} \lambda j}. \qquad \text{(B-142)}$$

B.6.1 Waiting Time Without Priority-Discipline

Consider first a M/M/1-FIFO system where there is only one priority class of traffic. In this system the mean system waiting time, $\overline{W}$, is given by

$$\overline{W} = \frac{1}{\mu - \lambda}, \qquad \text{(B-143)}$$

where μ is the mean message service rate and λ is the mean message arrival rate (reference 1). The probability that the system waiting time, W, will exceed t is given by (reference 1):

$$P(W > t) = e^{-(\mu - \lambda)t}. \qquad \text{(B-144)}$$

It is convenient to express $P(W > t)$ in terms of the mean system waiting time, $\overline{W}$. Comparing equations B-143 and B-144, it will be seen that equation B-144 can be written as

$$P(W > t) = e^{-t/\overline{W}}. \qquad \text{(B-145)}$$

Let us assume that a maximum desired system waiting time, W_m, is specified. From equation B-145, the probability of exceeding this maximum is

$$P(W > W_m) = e^{-W_m/\overline{W}}. \qquad \text{(B-146)}$$

Assume further that the maximum allowable probability of exceeding the maximum desired system waiting time, P_m, is also given. Then from equation B-146, we have

$$P_m = e^{-W_m/\overline{W}}. \qquad \text{(B-147)}$$

Solving for the mean system waiting time, $\overline{W}$, gives

$$\overline{W} \leq -W_{max}/\ln (P_m). \tag{B-148}$$

Thus it would be necessary to design a system with a mean system waiting time, $\overline{W}$, less than or equal to that given by equation B-148. The average message service rate required to achieve this waiting time can be found from equation B-143 as:

$$\mu = (1 + \lambda\overline{W})/\overline{W}. \tag{B-149}$$

The mean message duration is given by

$$\overline{X} = \overline{\ell}/r = 1/\mu , \tag{B-150}$$

where $\overline{\ell}$ is the mean message length in bits and r is the channel bit rate. From equations B-149 and B-150, the required minimum bit rate is found to be

$$r = \overline{\ell}(\lambda + 1/\overline{W}). \tag{B-151}$$

In some cases priority traffic may exist, but it is desired to handle this traffic without priority-discipline. In this case the system channel capacity as given by equation B-151 must be designed so that the maximum deisred system waiting time for the highest priority traffic, W_{m1}, is not exceeded with a probability greater than P_{m1} for all traffic. It follows that

$$\overline{W} \leq - W_{m1}/\ln(P_{m1}). \tag{B-152}$$

This generally requires a much higher channel capacity than required for a system employing priority-discipline.

B.6.2 Waiting Time With Priority-Discipline

Consider a single server (M/M/1) system with a single queue. Let us assume that when a new message enters the system, it is placed just ahead of the first message of the next lower priority class. The messages in queue will be arranged in priority classes with the highest priority class, 1, at the head of the queue, followed by classes 2, 3, ... i and N, where N is the lowest priority class. Within each priority class, the messages are served first-in, first-out (FIFO). When a priority 1 class message arrives, it is placed ahead of all lower class messages but behind all other first-priority messages already in the queue. If we assume that the arrival of a priority 1 message preempts lower priority message transmissions or that the time required to complete transmission of the lower priority message (which is in the process of being transmitted) is negligible, then it is clear that as far as first-priority traffic is concerned, the system behaves as if all lower priority traffic were absent. The probability, P_1, of exceeding the desired maximum system waiting time, W_{m1}, for first-priority messages is from equation B-144:

$$P_1 = e^{-W_{m1}(\mu - \lambda_1)}. \tag{B-153}$$

The average number of priority 1 messages which exceed the desired maximum waiting time per second is clearly

$$\overline{n}_1 = P_1 \lambda_1 , \tag{B-154}$$

so that the probability of a priority message waiting time exceeding the desired maximum can be written as

$$P_1 = \bar{n}_1 / \lambda_1 . \tag{B-155}$$

If we include all message priorities from 1 through i, then again the system will behave for these priority messages as if all lower priority (classes i + 1 through N) were absent.

The probability that the system waiting time for any of the priority classes 1 through i will exceed W_{mi}, therefore, is given by

$$P(W > W_{mi} \mid \text{message classes 1 through i}) = e^{-W_{mi}\left(\mu - \sum_{j=1}^{i} \lambda_i\right)} , \tag{B-156}$$

and the average number of messages per second of class 1 through i that exceed this waiting time is given by

$$\bar{n}_1 + \bar{n}_2 + \ldots \bar{n}_i = \sum_{j=1}^{i} \bar{n}_j = e^{-W_{mi}\left(\mu - \sum_{j=1}^{i} \lambda_j\right)} \cdot \sum_{j=1}^{i} \lambda_j . \tag{B-157}$$

The average number of messages per second of class 1 through i-1 which exceed a system waiting time of W_{mi} is

$$\bar{n}_1 + \bar{n}_2 \ldots + \bar{n}_{i-1} = \sum_{j=1}^{i-1} \bar{n}_j = e^{-W_{mi}\left(\mu - \sum_{j=1}^{i=1} \lambda_j\right)} \cdot \sum_{j=1}^{i=1} \lambda_j . \tag{B-158}$$

Subtracting equation B-158 from B-157 gives

$$\bar{n}_i = \sum_{j=1}^{i} \bar{n}_j - \sum_{j=1}^{i-1} \bar{n}_j = e^{-W_{mi}\mu} \, e^{W_{mi} \sum_{j=1}^{i-1} \lambda_j} \left[e^{W_{mi}\lambda_i} \sum_{j=1}^{i} \lambda_j - \sum_{j=1}^{i-1} \lambda_j \right] . \tag{B-159}$$

The probability of a class i message exceeding the desired maximum waiting time is therefore

$$P_i = \frac{\bar{n}_i}{\lambda_i} = e^{-W_{mi}\mu} \, e^{W_{mi} \sum_{j=1}^{i-1} \lambda_j} \left[\frac{\sum_{j=1}^{i} \lambda_j}{\lambda_i} \left(e^{W_{mi}\lambda_i} - 1 \right) + 1 \right] . \tag{B-160}$$

Solving equation B-160 for μ gives the minimum message service rate, μ_i, which will provide the desired probability of exceeding the desired maximum waiting time for priority class i messages.

$$\mu_i = \sum_{j=1}^{i-1} \lambda_j + \frac{1}{W_{mi}} \ln \left[\frac{\lambda_i + (e^{W_{mi}\lambda_i} - 1) \sum_{j=1}^{i} \lambda_j}{\lambda_i P_i} \right]. \tag{B-161}$$

Equation B-161 must be solved for each priority class, and the system must then be designed to provide a message service rate, μ_{max}, which is the highest of the resulting μ_i's. The corresponding required bit rate is

$$r = \bar{\ell}\, \mu_{max} . \tag{B-162}$$

The mean system waiting time, $\overline{W}$, is

$$\overline{W} = \frac{1}{\mu_{max} - \sum_{j=1}^{n_{max}} \lambda_j} . \tag{B-163}$$

B.7 REFERENCES

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C.1 INTRODUCTION

One of the most important criteria for ranking and evaluating demand assignment candidate techniques is total system cost. The DA technique that offers the highest performance could be prohibitively costly. The most desirable DA technique, therefore, is the one that offers the best performance at a cost commensurate with the user's budget. The approach of this appendix will be to analyze the cost of the highest ranked SHF DA candidates as determined during the final candidate selection process. Descriptions of each candidate will be given along with a block diagram which identifies the major system components. The following candidates will be included in this appendix:

a. Baseband Demand Assignment; Baseband Multiplex Technique: TDM; Multiple Access Technique: TDMA (BDA TDM-TDMA).
b. Baseband Demand Assignment; Baseband Multiplex Technique: TDM; Multiple Access Technique: FDMA (BDA FDM-TDMA).
c. Baseband Demand Assignment; Baseband Multiplex Technique: FDM; Multiple Access Technique: FDMA (BDA FDM-FDMA).
d. Demand Assignment Multiple Access; TDMA (DAMA-TDMA).
e. Demand Assignment Multiple Access; FDMA (DAMA-FDMA).

C.2 BDA TDM-TDMA

This BDA technique uses time-division multiplexing at baseband and a time-division multiple-access technique for its satellite link. The assignment at baseband is implemented by switched data traffic where common channel signaling is used. Two distinctive systems are considered, systems with TASI and systems without TASI. Each of the SHF users models will be priced individually.

Figure C-1 shows a typical block diagram of a BDA TDM-TDMA system. It is assumed that the baseband interface will be with a device similar to the TTC-39 digital switch. The input will be 16 kb/s channels of continuously variable slope delta modulated data appearing in the form of a TDM data stream.

The system will take the CVSD data, TTY data channels, and control channels and multiplex them into a single data channel. A variation of this system would include a TASI processor that would dynamically reassign channels during any change of its channel busy status. The TDM unit also contains protocol and channel reassignment circuitry that operates in conjunction with the system demand assignment processor. The processor controls and coordinates the assignment of all the available channels. It also provides proper coordination with destination processors both for message routing and timing.

Incoming data is conditioned by the data switch. From the data switch it goes to a baseband buffer unit that provides storage for incoming data to accommodate the difference between the data rate and transmission burst rate. From there the data is sent to the TDM multiplexer which assembles the data and then sends it to the burst modulator at the proper time. The TDM multiplexer controls all transmit system timing.

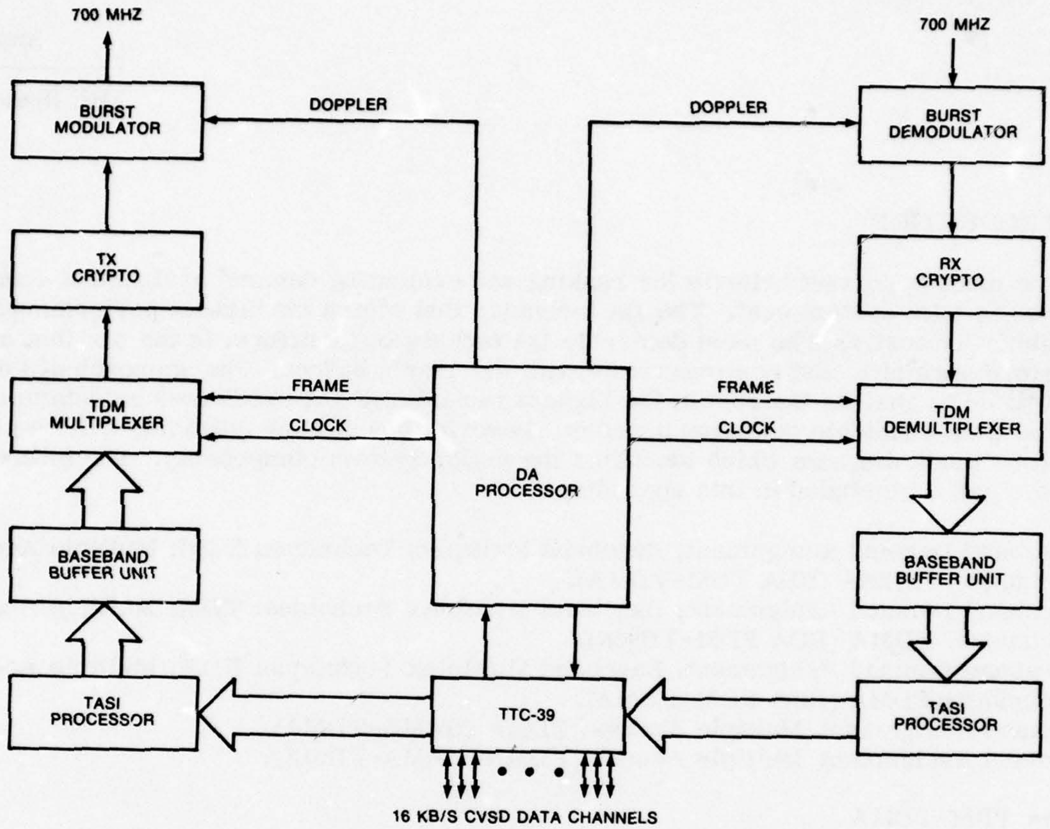

Figure C-1. BDA TDM-TDMA.

The satellite link for the TDMA system is a large TDM loop where each terminal has a fixed amount of permanently assigned capacity. The single channel data stream can be encrypted before the modulation process. However, it would be necessary to encrypt data at a 5- to 50-Mb/s data rate. This is given as an option and not included in the cost analysis. Another optional requirement is the need for a high-power transmitter and/or a high-gain antenna. The TDMA loop requires a system capable of large EIRP values. The receive section of this candidate is just the reverse process of the transmit section. It should be noted that only one receiver is needed to receive all net members.

C.2.1 Individual Unit Cost

The following paragraphs will consider each unit in terms of parts count, basis for cost estimate, unit cost, and estimated MTBF.

C.2.1.1 TASI Processor

The TASI processor can be implemented using a microprocessor using 16K words of memory and including line conditioning and high-speed switching capability. The estimated cost is $30,000. The parts count is estimated to be 2,000 pieces and the estimated MTBF is 1,000 hours. For larger systems, the cost of adding 8-channel increments is $1,500. The following tabulation shows the cost expansion:

NO. OF CHANNELS	COST
8	$30,000
16	31,500
32	34,500
64	40,500
128	52,500
256	76,500

C.2.1.2 Demand Assignment Processor

The demand assignment processor is a minicomputer that may contain up to 32K words of memory and a disc operating system (DOS) to provide capability for up to 256 channels of CVSD data. The cost is estimated by using a Rolm-1603 message processor with 16K words of memory. The cost is estimated to be $25,000 with an estimated cost of $2,000 per 1K words of additional memory and $24,000 for a DOS. The MTBF is estimated to be 260 hours for the basic system. The parts count is 6,100 pieces. The following tabulation shows the cost expansion:

NO. OF CHANNELS	SYSTEM	COST
Under 65	16K words	$25,000
65-128	32K words	$57,000
Over 128	32K words and DOS	$81,000

C.2.1.3 Baseband Buffer Unit

The baseband buffer unit operates in conjunction with the baseband data switch to provide data storage enabling the baseband and burst transmission rates to be substantially different. 8K bits of storage is required for every 10 Mb/s increment in the burst transmission rate. The cost of the baseband buffer unit is estimated to be $5,000, with each additional 8K words of storage costing $1500. The MTBF is estimated to be 5,000 hours based on a piece part count of 400 pieces. The following tabulation shows the cost expansion by user.

	USER	BURST RATE	COST
BDA-reservation w/o TASI	FLTOPS	2.1 Mb/s	$5,000
	GMF	34.6 Mb/s	$9,500
	DCS	17.4 Mb/s	$6,500
BDA-reservation with TASI	FLTOPS	1.8 Mb/s	$5,000
	GMF	18.2 Mb/s	$6,500
	DCS	8.7 Mb/s	$5,000
DAMA-reservation	FLTOPS	0.7 Mb/s	$5,000
	GMF	25.0 Mb/s	$8,000
	DCS	14.2 Mb/s	$6,500

C.2.1.4 Time-Division Mux/Demux Unit

The TDM unit contains the capability of multiplexing groups of 16 kb/s of CVSD data. It also contains an interface for the demand assignment processor to switch/select the channels to

be utilized. The cost of this unit is estimated to be $15,000, with additional channels costing $1,000 per 8 channels. The estimated MTBF is 4,000 hours for the basic unit. The estimated parts count is 4,000 pieces. The following tabulation shows the cost expansion:

NO. OF CHANNELS	COST
8	$15,000
16	$16,000
32	$18,000
64	$22,000
128	$30,000
256	$46,000

C.2.1.5 Burst Modulator/Demodulator

The burst modulator/demodulator provides the conversion from serial data to a modulated 700-MHz if signal and vice-versa. The QPSK modulator/demodulator must operate at speeds up to 34.6 Mb/s (for GMF). It is estimated to cost $15,000 and has an estimated MTBF of 6,800 hours based on containing 1,220 parts. It should be noted that the cost of the burst modem is highly dependent on specified acquisition time and waveform shaping. The estimated cost represents current modem technology with no special requirements for either parameter.

C.2.2 BDA TDM-TDMA Cost

BDA TDM-TDMA is sized and costed for FLTOPS, GMF, and DCS, both with and without TASI. The source of all traffic used for sizing is section 4 (User Models) of this report. The following matrix is provided to organize the sizing and cost tables for BDA TDM-TDMA.

BDA TDM-TDMA w/o TASI	FLTOPS	GMF	DCS
Sizing: Table No.	C-1	C-3	C-5
Cost Calculation: Table No.	C-2	C-4	C-6
BDA TDM-TDMA with TASI	**FLTOPS**	**GMF**	**DCS**
Sizing: Table No.	C-7	C-9	C-11
Cost Calculation: Table No.	C-8	C-10	C-12

Table C-1. FLTOPS, BDA TDM-TDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEM	BASEBAND BUFFER UNIT
			Qty	Size		
1	2	16	1	8	1	1
2	2	16	1	8	1	1
3	2	16	1	8	1	1
4	3	16	1	8	1	1
5	3	16	1	8	1	1
6	3	16	1	8	1	1
7	4	16	1	8	1	1
8	4	16	1	8	1	1
9	4	16	1	8	1	1
10	6	16	1	8	1	1
11	6	16	1	8	1	1
12	6	16	1	8	1	1
13	6	16	1	8	1	1
14	6	16	1	8	1	1
15	6	16	1	8	1	1
16	7	16	1	8	1	1
17	8	16	1	8	1	1
18	8	16	1	8	1	1
19	10	16	1	16	1	1
20	10	16	1	16	1	1
21	13	16	1	16	1	1
22	14	16	1	16	1	1

Table C-2. Cost for BDA TDM-TDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	18	8	$15,000	$ 270,000
	4	16	16,000	64,000
				$ 334,000*
Burst modem	22		$15,000	$ 330,000*
Processor and memory	22	16K words	$25,000	$ 550,000*
Baseband buffer unit	22		$ 5,000	$ 110,000*
Total				$1,324,000

*Denotes subtotal.

Table C-3. GMF, BDA TDM-TDMA System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	DA PROCESSOR (thousands of words)	TDM UNITS Qty	TDM UNITS Size	BURST MODEM	BASEBAND BUFFER UNIT
1	9	16	1	16	1	1
2	10	16	1	16	1	1
3	19	16	1	24	1	1
4	25	16	1	32	1	1
5	25	16	1	32	1	1
6	25	16	1	32	1	1
7	28	16	1	32	1	1
8	29	16	1	32	1	1
9	30	16	1	32	1	1
10	31	16	1	32	1	1
11	31	16	1	32	1	1
12	32	16	1	32	1	1
13	33	16	1	40	1	1
14	37	16	1	40	1	1
15	38	16	1	40	1	1
16	41	16	1	48	1	1
17	51	16	1	56	1	1
18	68	32	1	72	1	1
19	80	32	1	80	1	1
20	126	32	1	128	1	1

*The total system includes three of each of these terminals.

Table C-4. Cost for BDA TDM-TDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	2	16	$16,000	$ 32,000
	1	24	17,000	17,000
	9	32	18,000	162,000
	3	40	19,000	57,000
	1	48	20,000	20,000
	1	56	21,000	21,000
	1	72	23,000	23,000
	1	80	24,000	24,000
	1	128	30,000	30,000
				$ 386,000*
Burst modem	20		$15,000	$ 300,000*
Processor and memory	17	16K words	$25,000	$ 425,000
	3	32K words	57,000	171,000
				$ 596,000*
Baseband buffer unit	20		9,500	$ 190,000*
Total				$1,472,000
				x 3
Total system cost				$4,416,000
*Denotes subtotal.				

Table C-5. DCS, BDA TDM-TDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEM	BASEBAND BUFFER UNIT
			Qty	Size		
1	12	16	1	16	1	1
2	12	16	1	16	1	1
3	13	16	1	16	1	1
4	23	16	1	24	1	1
5	23	16	1	24	1	1
6	23	16	1	24	1	1
7	23	16	1	24	1	1
8	35	16	1	40	1	1
9	38	16	1	40	1	1
10	38	16	1	40	1	1
11	42	16	1	48	1	1
12	53	16	1	56	1	1
13	53	16	1	56	1	1
14	53	16	1	56	1	1
15	53	16	1	56	1	1
16	67	32	1	72	1	1
17	67	32	1	72	1	1
18	95	32	1	96	1	1
19	100	32	1	104	1	1
20	149	DOS	1	152	1	1
21	204	DOS	1	208	1	1

Table C-6. Cost for BDA TDM-TDMA, DCS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	3	16	$16,000	$ 48,000
	4	24	17,000	68,000
	3	40	19,000	57,000
	1	48	20,000	20,000
	4	56	21,000	84,000
	2	72	23,000	46,000
	1	96	26,000	26,000
	1	104	27,000	27,000
	1	152	33,000	33,000
	1	208	40,000	40,000
				$ 449,000*
Burst modem	21		$15,000	$ 315,000*
Processor and memory	15	16K words	$25,000	$ 375,000
	4	32K words	57,000	228,000
	2	DOS	81,000	162,000
				$ 765,000*
Baseband buffer unit	21		6,500	$ 136,500*
Total				$1,665,500

*Denotes subtotal.

Table C-7. FLTOPS, BDA TDM-TDMA (With TASI) System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	TASI PROCESSOR		DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEM	BASEBAND BUFFER UNIT
		Qty	Size		Qty	Size		
1	2	-		16	1	8	1	1
2	2	-		16	1	8	1	1
3	2	-		16	1	8	1	1
4	3	-		16	1	8	1	1
5	3	-		16	1	8	1	1
6	3	-		16	1	8	1	1
7	4	-		16	1	8	1	1
8	4	-		16	1	8	1	1
9	4	-		16	1	8	1	1
10	6	-		16	1	8	1	1
11	6	-		16	1	8	1	1
12	6	-		16	1	8	1	1
13	6	-		16	1	8	1	1
14	6	-		16	1	8	1	1
15	6	-		16	1	8	1	1
16	7	-		16	1	8	1	1
17	8	-		16	1	8	1	1
18	8	-		16	1	8	1	1
19	7	1	8	16	1	8	1	1
20	7	1	8	16	1	8	1	1
21	9	1	16	16	1	16	1	1
22	9	1	16	16	1	16	1	1

Table C-8. Cost for BDA With TASI, TDM-TDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	20	8	$15,000	$ 300,000
	2	16	16,000	32,000
				$ 332,000*
Burst modem	22		$15,000	$ 330,000*
Processor and memory	22	16K words	$25,000	$ 550,000*
TASI processor unit	2	8	$30,000	$ 60,000
	2	16	$31,500	63,000
				$ 123,000*
Baseband buffer unit	22		$ 5,000	$ 110,000*
Total				$1,445,000

*Denotes subtotal.

Table C-9. GMF, BDA TDM-TDMA (With TASI) System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	TASI PROCESSOR		DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEM	BASEBAND BUFFER UNIT
		Qty	Size		Qty	Size		
1	8	1	8	16	1	8	1	1
2	8	1	8	16	1	8	1	1
3	13	1	16	16	1	16	1	1
4	16	1	16	16	1	16	1	1
5	16	1	16	16	1	16	1	1
6	16	1	16	16	1	16	1	1
7	17	1	24	16	1	24	1	1
8	17	1	24	16	1	24	1	1
9	18	1	24	16	1	24	1	1
10	18	1	24	16	1	24	1	1
11	18	1	24	16	1	24	1	1
12	19	1	24	16	1	24	1	1
13	19	1	24	16	1	24	1	1
14	21	1	24	16	1	24	1	1
15	22	1	24	16	1	24	1	1
16	23	1	24	16	1	24	1	1
17	27	1	32	16	1	32	1	1
18	36	1	40	16	1	40	1	1
19	41	1	48	16	1	48	1	1
20	61	1	64	16	1	64	1	1

*The total system includes three of each of these terminals.

Table C-10. Cost for BDA With TASI, TDM-TDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	2	8	$15,000	$ 30,000
	4	16	16,000	64,000
	10	24	17,000	170,000
	1	32	18,000	18,000
	1	40	19,000	19,000
	1	48	20,000	20,000
	1	64	22,000	22,000
				$ 343,000*
Burst modem	20		$15,000	$ 300,000*
Processor and memory	20	16K words	$25,000	$ 500,000*
TASI processor unit	2	8	$30,000	$ 60,000
	4	16	31,500	126,000
	10	24	33,000	330,000
	1	32	34,500	34,500
	1	40	36,000	36,000
	1	48	37,500	37,500
	1	64	40,500	40,500
				$ 664,500*
Baseband buffer unit	20		$ 6,500	$ 130,000*
Total				$1,937,500
				x 3
Total system cost				$5,812,500
*Denotes subtotal				

Table C-11. DCS, BDA TDM-TDMA (With TASI) System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	TASI PROCESSOR		DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEM	BASEBAND BUFFER UNIT
		Qty	Size		Qty	Size		
1	9	1	16	16	1	16	1	1
2	9	1	16	16	1	16	1	1
3	10	1	16	16	1	16	1	1
4	15	1	16	16	1	16	1	1
5	15	1	16	16	1	16	1	1
6	15	1	16	16	1	16	1	1
7	15	1	16	16	1	16	1	1
8	20	1	24	16	1	24	1	1
9	22	1	24	16	1	24	1	1
10	22	1	24	16	1	24	1	1
11	23	1	24	16	1	24	1	1
12	29	1	32	16	1	32	1	1
13	29	1	32	16	1	32	1	1
14	29	1	32	16	1	32	1	1
15	35	1	40	16	1	40	1	1
16	35	1	40	16	1	40	1	1
17	47	1	48	16	1	48	1	1
18	47	1	48	16	1	48	1	1
19	49	1	56	16	1	56	1	1
20	71	1	72	32	1	72	1	1
21	94	1	96	32	1	96	1	1

Table C-12. Cost for BDA With TASI, TDM-TDMA, DCS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	7	16	$16,000	$ 112,000
	4	24	17,000	68,000
	3	32	18,000	54,000
	2	40	19,000	38,000
	2	48	20,000	40,000
	1	56	21,000	21,000
	1	72	23,000	23,000
	1	96	26,000	26,000
				$ 382,000*
Burst modem	21		$15,000	$ 315,000*
Processor and memory	19	16K words	$25,000	$ 475,000
	2	32K words	57,000	114,000
				$ 589,000*
TASI processor unit	7	16	$31,500	$ 220,500
	4	24	33,000	132,000
	3	32	34,500	103,500
	2	40	36,000	72,000
	2	48	37,500	75,000
	1	56	39,000	39,000
	1	72	42,000	42,000
	1	96	46,500	46,500
				$ 730,500*
Baseband buffer unit	21		5,000	$ 105,000*
Total				$2,121,500
*Denotes subtotal				

C.3 BDA TDM-FDMA

This BDA technique uses time-division multiplexing at baseband and a frequency-division multiple-access technique for its satellite link. Figure C-2 shows a typical block diagram for BDA TDM-FDMA. The system is very similar to the BDA TDM-TDMA system. However, because each terminal provides a separate carrier up to the satellite comprised of only the terminal's own input traffic, no baseband buffer unit is required to perform speed changes. The incoming, conditioned data from the data switch is routed directly to the TDM multiplexer, which puts the data in the proper time format and then passes the formatted data to the burst modulator. The burst modulator required for this candidate operates at a much slower rate than BDA TDM-TDMA (by a factor equal to 1/number of net users). The receive system provides the inverse function of the transmit side. However, it should be pointed out that a separate receive chain is required for each receive link at the terminal. Therefore, total interoperability will increase the cost of this candidate relative to all TDMA candidates. For cost purposes, each terminal is sized to provide the number of receive channels which is equal to the number of network members or which is equal to the number of terminal channels, whichever is smaller.

The baseband operation is identical to the previously described BDA TDM-TDMA. It contains the demand-assignment processor with its interface to the digital switch and the TDM unit. One DA processor is assumed capable of controlling all receiver systems.

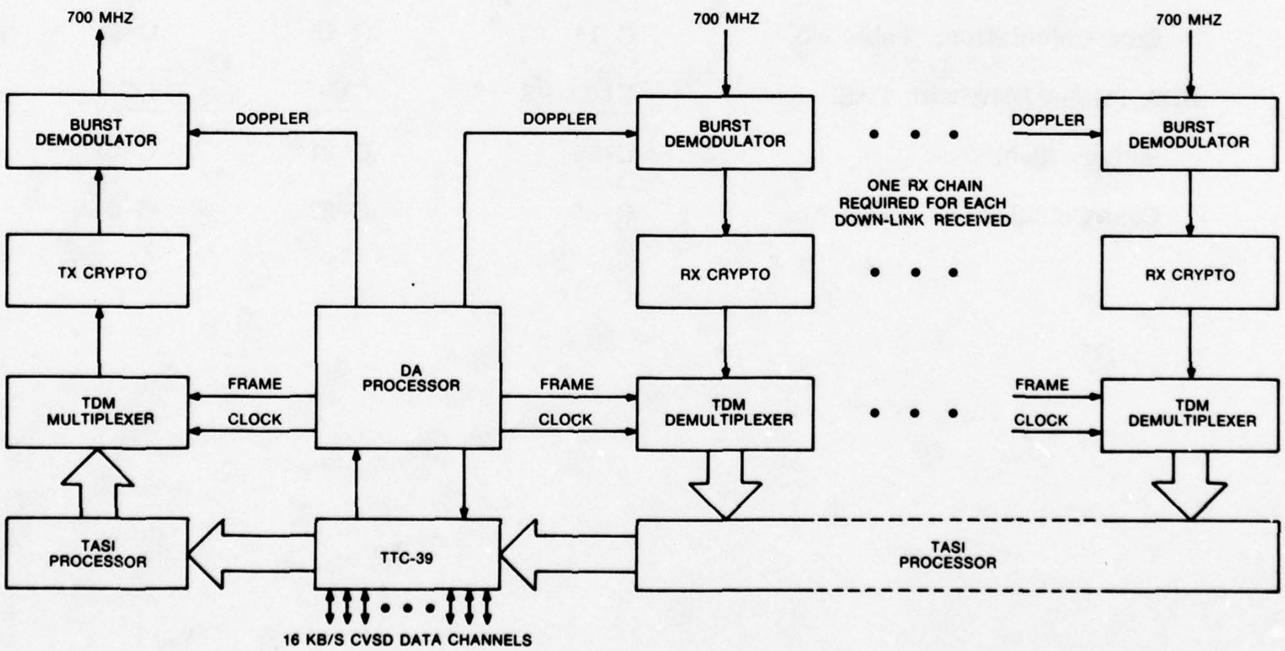

Figure C-2. BDA TDM-FDMA.

C.3.1 Individual Unit Cost

The individual elements that make up the BDA TDM-FDMA candidate are no different functionally than the elements that comprise the BDA TDM-TDMA candidate. Each performs identically for both candidates except for the burst modulator/demodulator, which operates on the average 1/n (n is number of net members) times slower for BDA TDM-FDMA. However, because each user has several members that require operation at burst rates much higher than the average, the same burst modulator/demodulator is included for both candidates. See paragraph C.2.1 and its subparagraphs for individual unit descriptions.

Each burst modulator/demodulator is built with an extra 700-MHz output so that multiple receive chains can be implemented without the addition of a signal splitter. Each receive chain requires a separate burst modulator/demodulator and TDM unit which, for commonality reasons, will contain unused transmit sections.

C.3.2 BDA TDM-FDMA

Each system will be sized and priced with and without TASI implementation. The cost analysis is repeated for FLTOPS, GMF, and DCS. The following matrix is provided to organize the sizing and costing of BDA TDM-FDMA:

BDA TDM-FDMA w/o TASI	FLTOPS	GMF	DCS
Sizing: Table No.	C-13	C-15	C-17
Cost Calculation: Table No.	C-14	C-16	C-18
BDA TDM-FDMA with TASI	**FLTOPS**	**GMF**	**DCS**
Sizing: Table No.	C-19	C-21	C-23
Cost Calculation: Table No.	C-20	C-22	C-24

Table C-13. FLTOPS, BDA TDM-FDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	RECEIVE CHAINS	DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEMS
				Qty	Size	
1	2	2	16	2	8	2
2	2	2	16	2	8	2
3	2	2	16	2	8	2
4	3	3	16	3	8	3
5	3	3	16	3	8	3
6	3	3	16	3	8	3
7	4	4	16	4	8	4
8	4	4	16	4	8	4
9	4	4	16	4	8	4
10	6	6	16	6	8	6
11	6	6	16	6	8	6
12	6	6	16	6	8	6
13	6	6	16	6	8	6
14	6	6	16	6	8	6
15	6	6	16	6	8	6
16	7	7	16	7	8	7
17	8	8	16	8	8	8
18	8	8	16	8	8	8
19	10	10	16	10	16	10
20	10	10	16	10	16	10
21	13	13	16	13	16	13
22	14	14	16	14	16	14

Table C-14. Cost for BDA TDM-FDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	86	8	$15,000	$1,290,000
	47	16	16,000	752,000
				$2,042,000*
Burst modem	133		$15,000	$1,995,000*
Processor and memory	22	16K words	$25,000	550,000*
Total				$4,587,000

*Denotes subtotal.

Table C-15. GMF, BDA TDM-FDMA System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	**RECEIVE CHAINS	DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEMS
				Qty	Size	
1	9	9	16	9	16	9
2	10	10	16	10	16	10
3	19	19	16	19	24	19
4	25	20	16	20	32	20
5	25	20	16	20	32	20
6	25	20	16	20	32	20
7	28	20	16	20	32	20
8	29	20	16	20	32	20
9	30	20	16	20	32	20
10	31	20	16	20	32	20
11	31	20	16	20	32	20
12	32	20	16	20	32	20
13	33	20	16	20	40	20
14	37	20	16	20	40	20
15	38	20	16	20	40	20
16	41	20	16	20	48	20
17	51	20	16	20	56	20
18	68	20	32	20	72	20
19	80	20	32	20	80	20
20	126	20	32	20	128	20

*The total system includes three of each of these terminals.
**Interoperability is required only within each corps.

Table C-16. Cost for BDA TDM-FDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	19	16	$16,000	$ 304,000
	19	24	17,000	323,000
	180	32	18,000	3,240,000
	60	40	19,000	1,140,000
	20	48	20,000	400,000
	20	56	21,000	420,000
	20	72	23,000	460,000
	20	80	24,000	480,000
	20	128	30,000	600,000
				7,367,000*
Burst modem	378		$15,000	$ 5,670,000*
Processor and memory	17	16K words	25,000	$ 425,000
	3	32K words	57,000	171,000
				$ 596,000*
Total				$13,633,000
				x 3
Total system cost				$40,899,000

*Denotes subtotal.

Table C-17. DCS, BDA TDM-FDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	RECEIVE CHAINS	DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEMS
				Qty	Size	
1	12	12	16	12	16	12
2	12	12	16	12	16	12
3	13	13	16	13	16	13
4	23	21	16	21	24	21
5	23	21	16	21	24	21
6	23	21	16	21	24	21
7	23	21	16	21	24	21
8	35	21	16	21	40	21
9	38	21	16	21	40	21
10	38	21	16	21	40	21
11	42	21	16	21	48	21
12	53	21	16	21	56	21
13	53	21	16	21	56	21
14	53	21	16	21	56	21
15	53	21	16	21	56	21
16	67	21	32	21	72	21
17	67	21	32	21	72	21
18	95	21	32	21	96	21
19	100	21	32	21	104	21
20	149	21	DOS	21	152	21
21	204	21	DOS	21	208	21

Table C-18. Cost for BDA TDM-FDMA, DCS.

TDM unit	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	37	16	$16,000	$ 592,000
	84	24	17,000	1,428,000
	63	40	19,000	1,197,000
	21	48	20,000	420,000
	84	56	21,000	1,764,000
	42	72	23,000	966,000
	21	96	26,000	546,000
	21	104	27,000	567,000
	21	152	33,000	693,000
	21	208	40,000	840,000
				$ 9,013,000*
Burst modem	415		$15,000	$ 6,225,000*
Processor and memory	15	16K words	25,000	$ 375,000
	4	32K words	57,000	228,000
	2	DOS	81,000	162,000
				$ 765,000*
Total				$16,003,000

*Denotes subtotal.

Table C-19. FLTOPS, BDA TDM-FDMA (With TASI) System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	RECEIVE CHAINS	TASI PROCESSOR		DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEMS
			Qty	Size		Qty	Size	
1	2	2			16	2	8	2
2	2	2			16	2	8	2
3	2	2			16	2	8	2
4	3	3			16	3	8	3
5	3	3			16	3	8	3
6	3	3			16	3	8	3
7	4	4			16	4	8	4
8	4	4			16	4	8	4
9	4	4			16	4	8	4
10	6	6			16	6	8	6
11	6	6			16	6	8	6
12	6	6			16	6	8	6
13	6	6			16	6	8	6
14	6	6			16	6	8	6
15	6	6			16	6	8	6
16	7	7			16	7	8	7
17	8	8			16	8	8	8
18	8	8			16	8	8	8
19	7	7	1	8	16	7	8	7
20	7	7	1	8	16	7	8	7
21	9	9	1	16	16	9	16	9
22	9	9	1	16	16	9	16	9

Table C-20. Cost for BDA With TASI, TDM-FDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	100	8	$15,000	$1,500,000
	18	16	16,000	288,000
				$1,788,000*
Burst modem	118		$15,000	$1,770,000*
Processor and memory	22	16K words	$25,000	$ 550,000*
TASI processor unit	2	8	$30,000	$ 60,000
	2	16	31,500	63,000
				$ 123,000*
Total				$4,231,000
*Denotes subtotal.				

Table C-21. GMF, BDA TDM-FDMA (With TASI) System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	**RECEIVE CHAINS	TASI PROCESSOR		DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEMS
			Qty	Size		Qty	Size	
1	8	8	1	8	16	8	8	8
2	8	8	1	8	16	8	8	8
3	13	13	1	16	16	13	16	13
4	16	16	1	16	16	16	16	16
5	16	16	1	16	16	16	16	16
6	16	16	1	16	16	16	16	16
7	17	17	1	24	16	17	24	17
8	17	17	1	24	16	17	24	17
9	18	18	1	24	16	18	24	18
10	18	18	1	24	16	18	24	18
11	18	18	1	24	16	18	24	18
12	19	19	1	24	16	19	24	19
13	19	19	1	24	16	19	24	19
14	21	20	1	24	16	20	24	20
15	22	20	1	24	16	20	24	20
16	23	20	1	24	16	20	24	20
17	27	20	1	32	16	20	32	20
18	36	20	1	40	16	20	40	20
19	41	20	1	48	16	20	48	20
20	61	20	1	64	16	20	64	20

*The total system includes three of each of these terminals.
**Interoperability is required only with each corps.

Table C-22. Cost for BDA With TASI, TDM-FDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	16	8	$15,000	$ 240,000
	61	16	16,000	976,000
	186	24	17,000	3,162,000
	20	32	18,000	360,000
	20	40	19,000	380,000
	20	48	20,000	400,000
	20	64	22,000	440,000
				$ 5,958,000*
Burst modem	343		$15,000	$ 5,145,000*
Processor and memory	20	16K words	$25,000	$ 500,000*
TASI processor unit	2	8	$30,000	$ 60,000
	4	16	31,500	126,000
	10	24	33,000	330,000
	1	32	34,500	34,500
	1	40	36,000	36,000
	1	48	37,500	37,500
	1	64	40,500	40,500
				$ 664,500*
Total				$12,268,000
				x 3
Total system cost				$36,803,000

*Denotes subtotal.

Table C-23. DCS, BDA TDM-FDMA (With TASI) System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	RECEIVE CHAINS	TASI PROCESSOR		DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEMS
			Qty	Size		Qty	Size	
1	9	9	1	16	16	9	16	9
2	9	9	1	16	16	9	16	9
3	10	10	1	16	16	10	16	10
4	15	15	1	16	16	15	16	15
5	15	15	1	16	16	15	16	15
6	15	15	1	16	16	15	16	15
7	15	15	1	16	16	15	16	15
8	20	20	1	24	16	20	24	20
9	22	21	1	24	16	21	24	21
10	22	21	1	24	16	21	24	21
11	23	21	1	24	16	21	24	21
12	29	21	1	32	16	21	32	21
13	29	21	1	32	16	21	32	21
14	29	21	1	32	16	21	32	21
15	35	21	1	40	16	21	40	21
16	35	21	1	40	16	21	40	21
17	47	21	1	48	16	21	48	21
18	47	21	1	48	16	21	48	21
19	49	21	1	56	16	21	56	21
20	71	21	1	72	32	21	72	21
21	94	21	1	96	32	21	96	21

Table C-24. Cost for BDA With TASI, TDM-FDMA, DCS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	88	16	$16,000	$ 1,408,000
	83	24	17,000	1,411,000
	63	32	18,000	1,134,000
	42	40	19,000	798,000
	42	48	20,000	840,000
	21	56	21,000	441,000
	21	72	23,000	483,000
	21	96	26,000	546,000
				$ 7,061,000*
Burst modem	381		$15,000	$ 5,715,000*
Processor and memory	19	16K words	$25,000	$ 475,000
	2	32K words	57,000	114,000
				$ 589,000*
TASI processor unit	7	16	$31,500	$ 220,500
	4	24	33,000	132,000
	3	32	34,500	103,500
	2	40	36,000	72,000
	2	48	37,500	75,000
	1	56	39,000	39,000
	1	72	43,500	43,500
	1	96	48,000	48,000
				$ 733,500*
Total				$14,098,500

*Denotes subtotal.

C.4 BDA FDM-FDMA

This BDA technique uses frequency-division multiplexing at baseband and a frequency-division multiple-access technique for its satellite link. The assignment at baseband is implemented by switched data traffic where common channel signaling is used. Two distinctive systems are considered, systems with TASI and systems without TASI.

Figure C-3 shows a typical block diagram of a BDA FDM-FDMA system. Since this system uses FDM instead of TDM for baseband multiplexing, each 16-kb/s CVSD channel is assigned its own rf carrier. The encryption units must be specified for 16-kb/s data. The demand assignment processor is required for message protocol and routing, but is not needed for link timing and synchronization because FDMA is used. It has nodal control through a control channel with other DA processors. By use of this common control channel between terminals, the DA processor can direct and receive traffic labeled with its address.

The baseband interface is assumed to be a digital switch similar to the TTC-39 whose input will be 16-kb/s channels of CVSD data. Each channel is routed into a modem that changes the data into a nominal 70-MHz carrier. This signal for each channel goes to a translator that has a synthesized local oscillator controlled by a reference frequency generator. It converts the carrier to a nominal frequency of 700 MHz. The exact frequency for each channel is under processor control and can be located anywhere in the SHF band. However, the

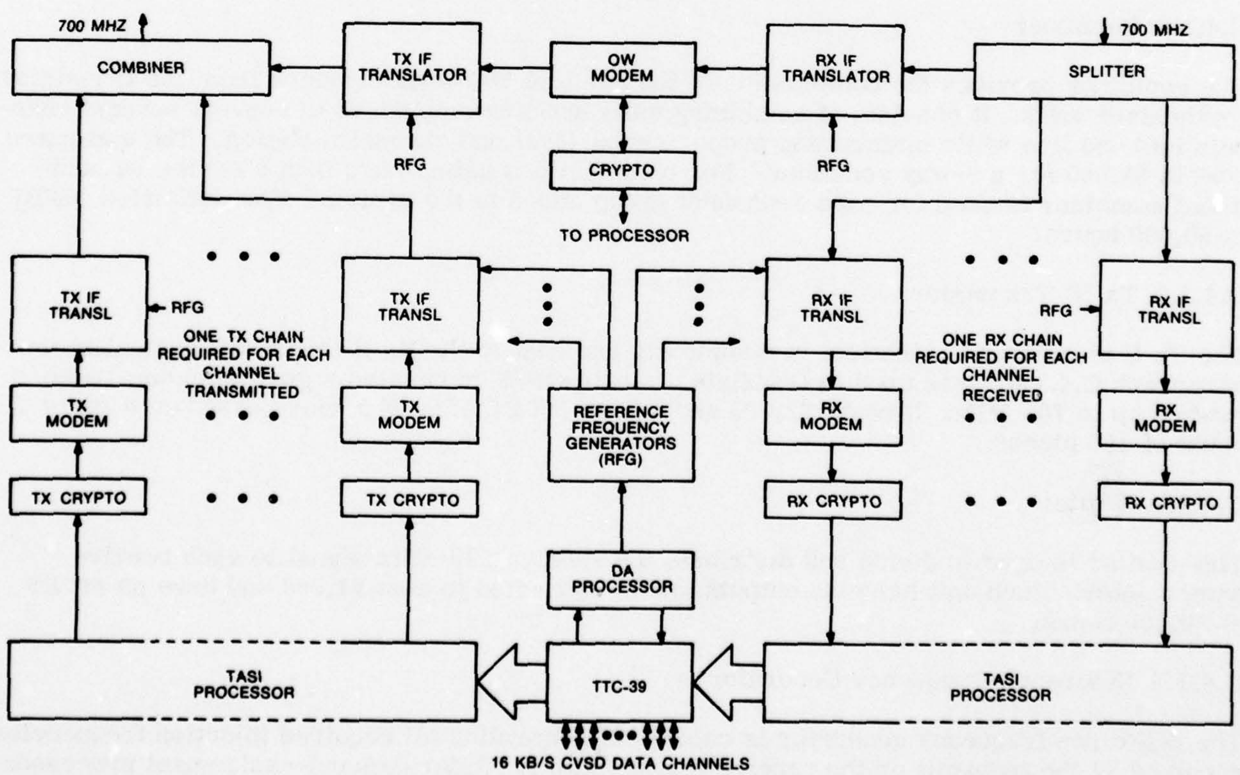

Figure C-3. BDA FDM-FDMA.

definition of BDA FDM-FDMA implies that the fixed-assigned rf up-link carriers of each terminal lie in contiguous rf channels. The separate carriers are then combined and passed on to the SHF up-converter for transmission.

The receive system is the complement of the transmit section. Each receive channel has to have the capability to tune anywhere in the assigned SHF band. This requires that a 700-MHz splitter be used in conjunction with individual if translators to provide the signal to each receive modem. One reference frequency generator can provide all necessary translation frequencies for transmit and receive.

C.4.1 Individual Unit Cost

The following paragraphs will consider each unit in terms of parts count, basis for cost estimate, unit cost, and estimated MTBF. For BDA FDM-FDMA the demand-assignment processor and the TASI processor are identical in hardware content to the units of like name in BDA TDM-TDMA and are described in paragraph C.2.1. Only the unique units will be described in the following paragraphs.

C.4.1.1 16 kb/s Modem

The 16-kb/s modem is used to convert 16-kb/s data into a QPSK modulated if signal at a nominal frequency of 70 MHz. On the receive side, it demodulates the if input into 16-kb/s data. One unit is required for each FDM channel and is estimated to cost $5,000. The estimated parts count is 1,050 pieces, and the estimated MTBF is 7,300 hours.

C.4.1.2 Combiner

The combiner provides the combination of the nominal 700-MHz carriers from the translator/ synthesizer units. It consists of combining units and line amplifiers to convert several channels into one line while maintaining proper signal level and channel isolation. The estimated cost is $1,000 for a 9-way combiner. For combinations using more than 9 inputs, an additional combiner is used for each 8-channel group added to the system. The estimated MTBF is 50,000 hours.

C.4.1.3 Tx IF Translator

The Tx if translator is identical in complexity and cost to the Rx if translator described in paragraph C.4.1.6. It is used to translate a single QPSK modulated signal from one 16-kb/s modem up to 700 MHz. It costs $2,000 and has an MTBF of 25,000 hours based on a parts count of 450 pieces.

C.4.1.4 Splitter

The splitter is used to divide and distribute the receive 700-MHz signal to each receive demodulator. Each unit has nine outputs and is estimated to cost $1,000 and have an MTBF of 50,000 hours.

C.4.1.5 Reference Frequency Generator

The reference frequency generator is capable of generating all required injection frequencies required by the transmit or the receive if translators. Under demand-assignment processor control, the RFG can provide the FDM channel offsets anywhere within the if passband. The RFG is estimated to cost $10,000 and have an MTBF of 4,000 hours based on 1,100 pieces.

C.4.1.6 Receive IF Translator

The receive if translator converts the 700-MHz first if frequency down to a single nominal 70-MHz frequency for the 16 kb/s modem. It receives its injection signals from the reference frequency generator. It is estimated to cost $2,000 and have an MTBF of 25,000 hours based on a parts count of 450 pieces.

C.4.2 BDA FDM-FDMA Cost

BDA FDM-FDMA is sized and costed individually for FLTOPS, GMF, and DCS, both with and without TASI. The following matrix is provided to organize the sizing and cost tables for BDA FDM-FDMA.

BDA FDM-FDMA w/o TASI	FLTOPS	GMF	DCS
Sizing: Table No.	C-25	C-27	C-29
Cost Calculation: Table No.	C-26	C-28	C-30
BDA FDM-FDMA with TASI	**FLTOPS**	**GMF**	**DCS**
Sizing: Table No.	C-31	C-33	C-35
Cost Calculation: Table No.	C-32	C-34	C-36

Table C-25. FLTOPS, BDA FDM-FDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	COMBINER / SPLITTER		REFERENCE FREQUENCY GENERATOR	DA PROCESSOR (thousands of words)	16-kb/s MODEM / RECEIVE IF TRANSLATOR / TRANSMIT IF TRANSLATOR
		Qty	Size			
1	2	1	9	1	16	2
2	2	1	9	1	16	2
3	2	1	9	1	16	2
4	3	1	9	1	16	3
5	3	1	9	1	16	3
6	3	1	9	1	16	3
7	4	1	9	1	16	4
8	4	1	9	1	16	4
9	4	1	9	1	16	4
10	6	1	9	1	16	6
11	6	1	9	1	16	6
12	6	1	9	1	16	6
13	6	1	9	1	16	6
14	6	1	9	1	16	6
15	6	1	9	1	16	7
16	7	1	9	1	16	8
17	8	1	9	1	16	8
18	8	1	9	1	16	10
19	10	1	17	1	16	10
20	10	1	17	1	16	10
21	13	1	17	1	16	13
22	14	1	17	1	16	14

Table C-26. Cost for BDA FDM-FDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
16-kb/s modem	137		$ 5,000	$ 685,000*
Processor and memory	22	16K words	$25,000	$ 550,000*
Transmit if translator	137		$ 2,000	$ 274,000*
Combiner	18	9	$ 1,000	$ 18,000
	4	17	2,000	8,000
				$ 26,000*
Reference frequency generator	22		$10,000	$ 220,000*
Splitter	18	9	$ 1,000	$ 18,000
	4	17	2,000	8,000
				26,000*
Receive if translator	137		$ 2,000	$ 274,000*
Total				$2,055,000

*Denotes subtotal.

Table C-27. GMF, BDA FDM-FDMA System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	COMBINER / SPLITTER Qty	COMBINER / SPLITTER Size	REFERENCE FREQUENCY GENERATOR	DA PROCESSOR (thousands of words)	16-kb/s MODEM / RECEIVE IF TRANSLATOR / TRANSMIT IF TRANSLATOR
1	9	1	9	1	16	9
2	10	1	17	1	16	10
3	19	1	25	1	16	19
4	25	1	25	1	16	25
5	25	1	25	1	16	25
6	25	1	25	1	16	25
7	28	1	33	1	16	28
8	29	1	33	1	16	29
9	30	1	33	1	16	30
10	31	1	33	1	16	31
11	31	1	33	1	16	31
12	32	1	33	1	16	32
13	33	1	33	1	16	33
14	37	1	41	1	16	37
15	38	1	41	1	16	38
16	41	1	41	1	16	41
17	51	1	57	1	16	51
18	68	1	73	1	32	68
19	80	1	81	1	32	80
20	126	1	129	1	32	126

*The total system includes three of each of these terminals.

Table C-28. Cost for BDA FDM-FDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
16-kb/s modem	768		$ 5,000	$ 3,840,000*
Processor and memory	17	16K words	$25,000	$ 425,000
	3	32K words	57,000	171,000
				$ 596,000*
Transmit if translator	768		$ 2,000	$ 1,536,000*
Combiner	1	9	$ 1,000	$ 1,000
	1	17	2,000	2,000
	4	25	3,000	12,000
	7	33	4,000	28,000
	3	41	5,000	15,000
	1	57	7,000	7,000
	1	73	9,000	9,000
	1	81	10,000	10,000
	1	129	11,000	11,000
				$ 95,000*
Reference frequency generator	20		$10,000	$ 200,000*
Receive if translator	768		$ 2,000	$ 1,536,000*
Splitter	1	9	$ 1,000	$ 1,000
	1	17	2,000	2,000
	4	25	3,000	12,000
	7	33	4,000	28,000
	3	41	5,000	15,000
	1	57	7,000	7,000
	1	73	9,000	9,000
	1	81	10,000	10,000
	1	129	11,000	11,000
				$ 95,000*
Total				$ 7,898,000
				x 3
Total system cost				$23,694,000

*Denotes subtotal.

Table C-29. DCS, BDA FDM-FDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	COMBINER / SPLITTER		REFERENCE FREQUENCY GENERATOR	DA PROCESSOR (thousands of words)	16-kb/s MODEM / RECEIVE IF TRANSLATOR / TRANSMIT IF TRANSLATOR
		Qty	Size			
1	12	1	17	1	16	12
2	12	1	17	1	16	12
3	13	1	17	1	16	13
4	23	1	25	1	16	23
5	23	1	25	1	16	23
6	23	1	25	1	16	23
7	23	1	25	1	16	23
8	35	1	41	1	16	35
9	38	1	41	1	16	38
10	38	1	41	1	16	38
11	42	1	49	1	16	42
12	53	1	57	1	16	53
13	53	1	57	1	16	53
14	53	1	57	1	16	53
15	53	1	57	1	16	53
16	67	1	73	1	32	67
17	67	1	73	1	32	67
18	95	1	97	1	32	95
19	100	1	105	1	32	100
20	149	1	153	1	DOS	149
21	204	1	209	1	DOS	204

Table C-30. Cost for BDA FDM-FDMA, DCS.

UNIT TYPE	QUANTITY Qty	QUANTITY Size	UNIT COST	TOTAL COST
16 kb/s modem	1176		$ 5,000	$ 5,880,000*
Processor and memory	15	16K words	$25,000	$ 375,000
	4	32K words	57,000	228,000
	2	DOS	81,000	162,000
				765,000*
Transmit if translator	1176		$ 2,000	$ 2,352,000*
Combiner	3	17	$ 2,000	$ 6,000
	4	25	3,000	12,000
	3	41	5,000	15,000
	1	49	6,000	6,000
	4	57	7,000	28,000
	2	73	9,000	18,000
	1	97	12,000	12,000
	1	105	13,000	13,000
	1	153	19,000	19,000
	1	209	26,000	26,000
				$ 155,000*
Reference frequency generator	21		$10,000	$ 210,000*
Receive if translator	1176		$ 2,000	$ 2,352,000*
Splitter	3	17	$ 2,000	$ 6,000
	4	25	3,000	12,000
	3	41	5,000	15,000
	1	49	6,000	6,000
	4	57	7,000	28,000
	2	73	9,000	18,000
	1	97	12,000	12,000
	1	105	13,000	13,000
	1	153	19,000	19,000
	1	209	26,000	26,000
				$ 155,000*
Total				$11,869,000

*Denotes subtotal.

Table C-31. FLTOPS, BDA FDM-FDMA (With TASI) System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	COMBINER / SPLITTER		TASI PROCESSOR		DA PROCESSOR (thousands of words)	REFERENCE FREQUENCY GENERATOR	16-kb/s MODEM / RECEIVE IF TRANSLATOR / TRANSMIT IF TRANSLATOR
		Qty	Size	Qty	Size			
1	2	1	9			16	1	2
2	2	1	9			16	1	2
3	2	1	9			16	1	2
4	3	1	9			16	1	3
5	3	1	9			16	1	3
6	3	1	9			16	1	3
7	4	1	9			16	1	4
8	4	1	9			16	1	4
9	4	1	9			16	1	4
10	6	1	9			16	1	6
11	6	1	9			16	1	6
12	6	1	9			16	1	6
13	6	1	9			16	1	6
14	6	1	9			16	1	6
15	6	1	9			16	1	6
16	7	1	9			16	1	7
17	8	1	9			16	1	8
18	8	1	9			16	1	8
19	7	1	9	1	8	16	1	7
20	7	1	9	1	8	16	1	7
21	9	1	9	1	16	16	1	9
22	9	1	9	1	16	16	1	9

Table C-32. Cost for BDA With TASI, FDM-FDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
16 kb/s modem	118		$ 5,000	$ 590,000*
Processor and memory	22	16K words	$25,000	$ 550,000*
TASI processor	2 2	8 16	$30,000 31,500	$ 60,000 63,000 $123,000*
Transmit if translator	118		$ 2,000	$ 236,000*
Combiner	22	9	$ 1,000	$ 22,000*
Reference frequency generator	22		$10,000	$ 220,000*
Receive if translator	118		$ 2,000	$ 236,000*
Splitter	22	9	$ 1,000	$ 22,000*
Total				$1,999,000
*Denotes subtotal.				

Table C-33. GMF, BDA FDM-FDMA (With TASI) System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	COMBINER SPLITTER		TASI PROCESSOR		DA PROCESSOR (thousands of words)	REFERENCE FREQUENCY GENERATOR	16-kb/s MODEM / RECEIVE IF TRANSLATOR / TRANSMIT IF TRANSLATOR
		Qty	Size	Qty	Size			
1	8	1	9	1	8	16	1	8
2	8	1	9	1	8	16	1	8
3	13	1	17	1	16	16	1	13
4	16	1	17	1	16	16	1	16
5	16	1	17	1	16	16	1	16
6	16	1	17	1	16	16	1	16
7	17	1	17	1	24	16	1	17
8	17	1	17	1	24	16	1	17
9	18	1	25	1	24	16	1	18
10	18	1	25	1	24	16	1	18
11	18	1	25	1	24	16	1	18
12	19	1	25	1	24	16	1	19
13	19	1	25	1	24	16	1	19
14	21	1	25	1	24	16	1	21
15	22	1	25	1	24	16	1	22
16	23	1	25	1	24	16	1	23
17	27	1	33	1	32	16	1	27
18	36	1	41	1	40	16	1	36
19	41	1	41	1	48	16	1	41
20	61	1	65	1	64	16	1	61

*The total system includes three of each of these terminals.

Table C-34. Cost for BDA With TASI, FDM-FDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
16-kb/s modem	434		$ 5,000	$ 2,170,000*
Processor and memory	20	16K words	$25,000	$ 500,000*
TASI processor	2	8	$30,000	$ 60,000
	4	16	31,500	126,000
	10	24	33,000	330,000
	1	32	34,500	34,500
	1	40	36,000	36,000
	1	48	37,500	37,500
	1	64	40,500	40,500
				$ 664,500*
Transmit if translator	434		$ 2,000	$ 868,000*
Combiner	2	9	$ 1,000	$ 2,000
	6	17	2,000	12,000
	8	25	3,000	24,000
	1	33	4,000	4,000
	2	41	5,000	10,000
	1	65	8,000	8,000
				$ 60,000*
Reference frequency generator	20		$10,000	$ 200,000*
Receive if translator	434		$ 2,000	$ 868,000*
Splitter	2	9	$ 1,000	$ 2,000
	6	17	2,000	12,000
	8	25	3,000	24,000
	1	33	4,000	4,000
	2	41	5,000	10,000
	1	65	8,000	8,000
				$ 60,000*
Total				$ 5,390,500
				x 3
Total system cost				$16,171,500
*Denotes subtotal.				

Table C-35. DCS, BDA FDM-FDMA (With TASI) System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	COMBINER SPLITTER		TASI PROCESSOR		DA PROCESSOR (thousands of words)	REFERENCE FREQUENCY GENERATOR	16-kb/s MODEM / RECEIVE IF TRANSLATOR / TRANSMIT IF TRANSLATOR
		Qty	Size	Qty	Size			
1	9	1	9	1	16	16	1	9
2	9	1	9	1	16	16	1	9
3	10	1	17	1	16	16	1	10
4	15	1	17	1	16	16	1	15
5	15	1	17	1	16	16	1	15
6	15	1	17	1	16	16	1	15
7	15	1	17	1	16	16	1	15
8	20	1	25	1	24	16	1	20
9	22	1	25	1	24	16	1	22
10	22	1	25	1	24	16	1	22
11	23	1	25	1	24	16	1	23
12	29	1	33	1	32	16	1	29
13	29	1	33	1	32	16	1	29
14	29	1	33	1	32	16	1	29
15	35	1	41	1	40	16	1	35
16	35	1	41	1	40	16	1	35
17	47	1	49	1	48	16	1	47
18	47	1	49	1	48	16	1	47
19	49	1	49	1	56	16	1	49
20	71	1	73	1	72	32	1	71
21	94	1	97	1	96	32	1	94

Table C-36. Cost for BDA With TASI, FDM-FDMA, DCS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
16-kb/s modem	640		$ 5,000	$3,200,000*
Processor and memory	19	16K words	$25,000	$ 475,000
	2	32K words	57,000	114,000
				$ 589,000*
TASI processor	7	16	$31,500	$ 220,500
	4	24	33,000	132,000
	3	32	34,500	103,500
	2	40	36,000	72,000
	2	48	37,500	75,000
	1	56	39,000	39,000
	1	72	42,000	42,000
	1	96	46,500	46,500
				$ 730,500*
Transmit if translator	640		$ 2,000	$1,280,000*
Combiner	2	9	$ 1,000	$ 2,000
	5	17	2,000	10,000
	4	25	3,000	12,000
	3	33	4,000	12,000
	2	41	5,000	10,000
	3	49	6,000	18,000
	1	73	9,000	9,000
	1	97	12,000	12,000
				$ 85,000*
Reference frequency generator	21		$10,000	$ 210,000*
Receive if translator	640		$ 2,000	$1,280,000*
Splitter	2	9	$ 1,000	$ 2,000
	5	17	$ 2,000	10,000
	4	25	3,000	12,000
	3	33	4,000	12,000
	2	41	5,000	10,000
	3	49	6,000	18,000
	1	73	9,000	9,000
	1	97	12,000	12,000
				$ 85,000*
Total				$7,459,500
*Denotes subtotal.				

C.5 DAMA-TDMA

This DAMA technique uses time-division to multiple access the satellite and is very similar to BDA TDM-TDMA. The difference between the two candidates is that BDA TDM-TDMA assigns on demand the fixed terminal rf capacity to its individual subscribers where DAMA-TDMA assigns the satellite capacity on demand to any terminal subscriber requiring service. The block diagram for either candidate is the same and is shown in figure C-1. The base-board interface is assumed to be a digital switch similar to the TTC-39. The inputs from each subscriber will be 16 kb/s CVSD data. Each channel flows through the digital switch to a buffer unit where the necessary speed changing occurs. From there the data is sent to the TDM unit for time formatting into a single high-speed data stream. Then, when capacity is assigned to the user by the processor, the data is sent to the burst modulator for transmission to the satellite. The burst modulator must be capable of data rates up to 50 mb/s. DAMA-TDMA requires a large EIRP to provide the high-speed data transmissions. The demand assignment processor is responsible for the sequencing of the 16-kb/s channels on the high-speed data loop and the correct routing of the demultiplexed channels. Encryption is possible at the high-speed data interface. The encryption unit must be capable of operation at the burst rate. The receive system is the complement of the transmit equipment.

C.5.1 Individual Unit Cost

All of the units that make up a DAMA-TDMA system are functionally similar to the units making up BDA TDM-TDMA. Descriptions of these units can be found in paragraph C.2.1 and its subparagraphs. The operational differences between DAMA-TDMA and BDA TDM-TDMA do not affect the cost of the units.

C.5.2 DAMA-TDMA Cost

DAMA-TDMA is sized and costed individually for FLTOPS, GMF, and DCS. The following matrix is provided to organize the tables with numbers C-37 through C-42:

	FLTOPS	GMF	DCS
Sizing: Table No.	C-37	C-39	C-41
Cost Calculation: Table No.	C-38	C-40	C-42

Table C-37. FLTOPS, DAMA-TDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEMS		BASEBAND BUFFER UNIT
			Qty	Size	Qty	Size	
1	3	16	1	8	1		1
2	3	16	1	8	1		1
3	4	16	1	8	1		1
4	5	16	1	8	1		1
5	5	16	1	8	1		1
6	5	16	1	8	1		1
7	5	16	1	8	1		1
8	6	16	1	8	1		1
9	6	16	1	8	1		1
10	6	16	1	8	1		1
11	6	16	1	8	1		1
12	6	16	1	8	1		1
13	7	16	1	8	1		1
14	7	16	1	8	1		1
15	7	16	1	8	1		1
16	7	16	1	8	1		1
17	8	16	1	8	1		1
18	9	16	1	16	1		1
19	11	16	1	16	1		1
20	11	16	1	16	1		1
21	15	16	1	16	1		1
22	16	16	1	16	1		1

Table C-38. Cost for DAMA-TDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	17	8	$15,000	$ 255,000
	5	16	16,000	$ 80,000
				$ 335,000*
Burst modem	22		$15,000	$ 330,000*
Processor and memory	22	16K words	$25,000	$ 550,000*
Baseband buffer unit	22		$ 5,000	$ 110,000*
Total				$1,325,000

*Denotes subtotal.

Table C-39. GMF, DAMA-TDMA System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	DA PROCESSOR (thousands of words)	TDM UNITS		BURST MODEM	BASEBAND BUFFER UNIT
			Qty	Size		
1	10	16	1	16	1	1
2	11	16	1	16	1	1
3	21	16	1	24	1	1
4	27	16	1	32	1	1
5	28	16	1	32	1	1
6	28	16	1	32	1	1
7	30	16	1	32	1	1
8	32	16	1	32	1	1
9	33	16	1	40	1	1
10	33	16	1	40	1	1
11	34	16	1	40	1	1
12	35	16	1	40	1	1
13	36	16	1	40	1	1
14	40	16	1	40	1	1
15	41	16	1	48	1	1
16	45	16	1	48	1	1
17	56	16	1	56	1	1
18	74	32	1	80	1	1
19	87	32	1	88	1	1
20	135	DOS	1	136	1	1

*The total system includes three of each of these terminals.

Table C-40. Cost for DAMA-TDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	2	16	$16,000	$ 32,000
	1	24	17,000	17,000
	5	32	18,000	90,000
	6	40	19,000	114,000
	2	48	20,000	40,000
	1	56	21,000	21,000
	1	80	24,000	24,000
	1	88	25,000	25,000
	1	136	31,000	31,000
				$ 394,000*
Burst modem	20		$15,000	$ 300,000*
Processor and memory	17	16K words	$25,000	$ 425,000
	2	32K words	57,000	114,000
	1	DOS	81,000	81,000
				$ 620,000*
Baseband buffer unit	20		$ 8,000	$ 160,000*
Total				$1,474,000
				x 3
Total system cost				$4,422,000

*Denotes subtotal.

Table C-41. DCS, DAMA-TDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	DA PROCESSOR (thousands of words)	TDM UNIT		BURST MODEM	BASEBAND BUFFER UNIT
			Qty	Size		
1	13	16	1	16	1	1
2	13	16	1	16	1	1
3	15	16	1	16	1	1
4	25	16	1	32	1	1
5	25	16	1	32	1	1
6	25	16	1	32	1	1
7	25	16	1	32	1	1
8	37	16	1	40	1	1
9	41	16	1	48	1	1
10	41	16	1	48	1	1
11	45	16	1	48	1	1
12	57	16	1	56	1	1
13	57	16	1	56	1	1
14	57	16	1	56	1	1
15	57	16	1	56	1	1
16	71	32	1	72	1	1
17	71	32	1	72	1	1
18	103	32	1	104	1	1
19	108	32	1	112	1	1
20	157	DOS	1	160	1	1
21	213	DOS	1	216	1	1

Table C-42. Cost for DAMA-TDMA, DCS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
TDM unit	3	16	$16,000	$ 48,000
	4	32	18,000	72,000
	1	40	19,000	19,000
	3	48	20,000	60,000
	4	56	21,000	84,000
	2	72	23,000	46,000
	1	104	27,000	27,000
	1	112	28,000	28,000
	1	160	34,000	34,000
	1	216	41,000	41,000
				$ 459,000*
Burst modem	21		15,000	$ 315,000*
Processor and memory	15	16K words	25,000	$ 375,000
	4	32K words	57,000	228,000
	2	DOS	81,000	162,000
				$ 765,000*
Baseband buffer unit	21		6,500	$ 136,500*
Total				$1,675,500

*Denotes subtotal.

C.6 DAMA-FDMA

This DAMA technique uses frequency-division multiple access to the satellite. The VOX option is priced separately for each of the user models considered. Figure C-4 shows a typical block diagram of a DAMA-FDMA system. The baseband interface is assumed to be a digital switch similar to the TTC-39 whose input will be 16-kb/s channels of CVSD data. Each channel is routed through an optional VOX processor into a modem. The modem changes the data into a nominal 70-MHz carrier. This signal for each channel goes to a translator that has a synthesized local oscillator controlled by a reference frequency generator. It converts the carrier to a nominal frequency of 700 MHz. The exact frequency for each channel is under processor control and can be located anywhere in the SHF band. The separate carriers are then combined and passed on to the SHF up-converter for transmission. Encryption is possible for each channel before the data is converted to rf. The specification of the encryption unit must include the capability for 16-kb/s data. The receive system is the complement of the transmit section.

DAMA-FDMA is very similar to BDA FDM-FDMA in that each 16 kb/s data channel forms a separate rf carrier both to and from the satellite. However, in BDA FDM-FDMA each terminal has a fixed amount of contiguous rf channels that are shared among the terminal's subscribers on a demand basis. The rf relationship (frequency) of the up-link channels is fixed. DAMA-FDMA differs in that the rf capacity of the satellite is shared among all subscribers of all terminals on a demand basis. Further, the rf relationship of the up-link channels at any terminal changes from assignment to assignment and therefore requires a more capable up-link frequency translator system. The receive section of each candidate is identical because the rf frequency relationship of the down-link channels depends on call destination. Each candidate requires the same number of receive channels.

C.6.1 Individual Unit Cost

The following paragraphs will consider each unit in terms of parts count, basis for estimating cost, unit cost, and estimated MTBF. The splitter, combiner, Rx and Tx if translator, 16 kb/s modem, reference frequency generator, and demand assignment processor are identical to the units in BDA FDM-FDMA and descriptions of these units can be found in paragraph C.4.1 and its subparagraphs.

C.6.1.1 VOX Processor

The VOX processor is a dynamic switch that responds to breaks in the data (pauses in the speech) and removes the rf carrier during these breaks. It has a fast response and attack time in order to not degrade channel performance. Its cost is estimated to be $15,000 for a basic 8-channel unit. Each additional 8-channel group will cost approximately $3,000. The estimated parts count is 1,600 pieces, and the MTBF is estimated to be 1,000 hours. The following tabulation shows the cost expansion:

NO. OF CHANNELS	COST
8	$ 15,000
16	18,000
32	24,000
64	36,000
128	60,000
256	108,000

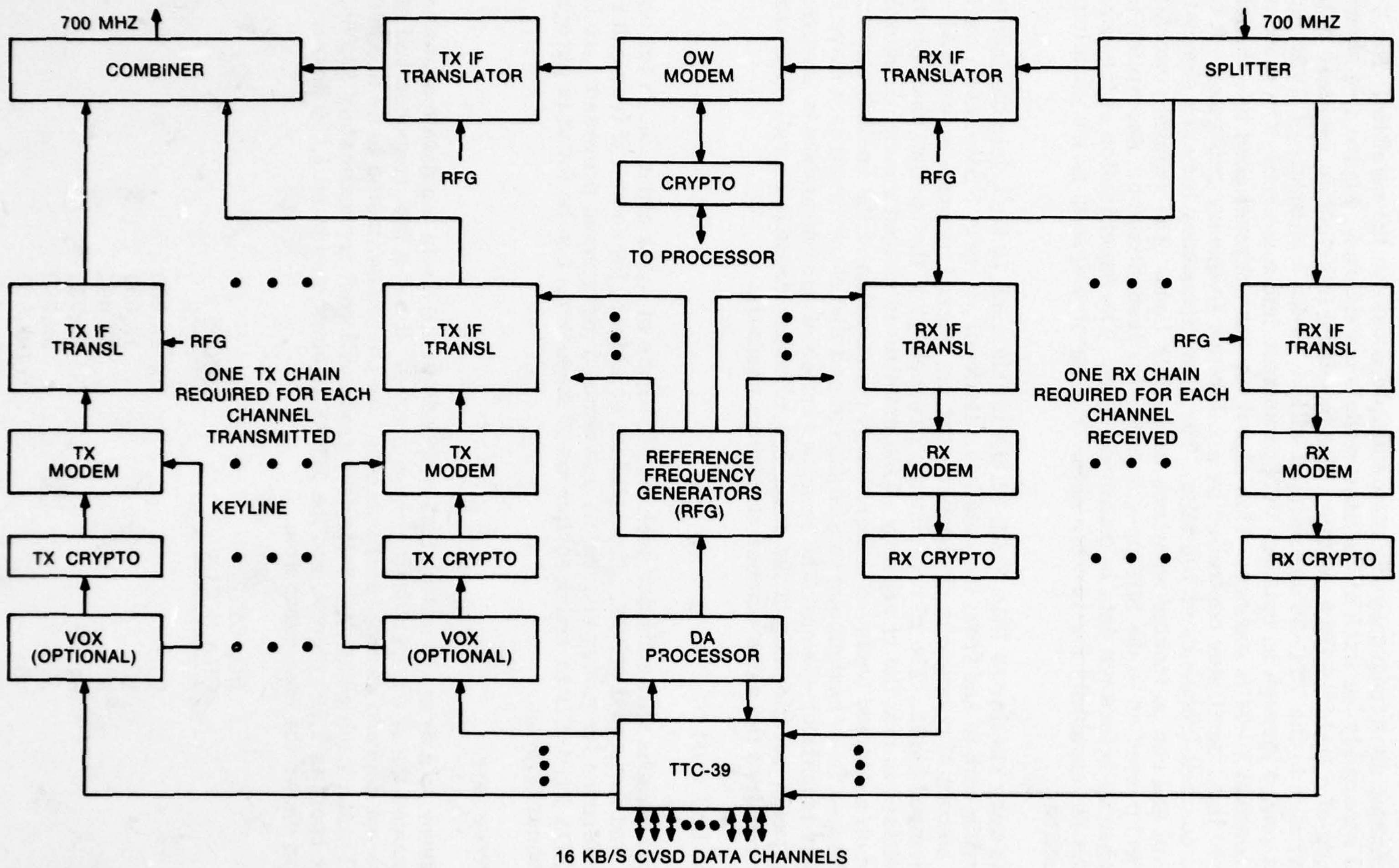

Figure C-4. DAMA-FDMA.

C.6.2 DAMA-FDMA Costs

DAMA-FDMA is sized and costed separately for FLTOPS, GMF, and DCS. Systems are tabulated with the cost excluding the VOX option. The cost of the option is listed separately. The following matrix is provided to organize the tables with numbers C-43 through C-48:

	FLTOPS	GMF	DCS
Sizing: Table No.	C-43	C-45	C-47
Cost Calculation: Table No.	C-44	C-46	C-48

Table C-43. FLTOPS, DAMA-FDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	VOX PROCESSOR		DA PROCESSOR (thousands of words)	IF TRANSLATOR		16-kb/s MODEM	SPLITTER COMBINER		REFERENCE FREQUENCY GENERATOR
		Qty	Size		Tx	Rx		Qty	Size	
1	3	1	8	16	3	3	3	1	9	1
2	3	1	8	16	3	3	3	1	9	1
3	4	1	8	16	4	4	4	1	9	1
4	5	1	8	16	5	5	5	1	9	1
5	5	1	8	16	5	5	5	1	9	1
6	5	1	8	16	5	5	5	1	9	1
7	5	1	8	16	5	5	5	1	9	1
8	6	1	8	16	6	6	6	1	9	1
9	6	1	8	16	6	6	6	1	9	1
10	6	1	8	16	6	6	6	1	9	1
11	6	1	8	16	6	6	6	1	9	1
12	6	1	8	16	6	6	6	1	9	1
13	7	1	8	16	7	7	7	1	9	1
14	7	1	8	16	7	7	7	1	9	1
15	7	1	8	16	7	7	7	1	9	1
16	7	1	8	16	7	7	7	1	9	1
17	8	1	8	16	8	8	8	1	9	1
18	9	1	16	16	9	9	9	1	9	1
19	11	1	16	16	11	11	11	1	17	1
20	11	1	16	16	11	11	11	1	17	1
21	15	1	16	16	15	15	15	1	17	1
22	16	1	16	16	16	16	16	1	17	1

Table C-44. Cost for DAMA-FDMA, FLTOPS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
Tx if translator	158		$ 2,000	$ 316,000*
Rx if translator	158		$ 2,000	$ 316,000*
16-kb/s modem	158		$ 5,000	$ 790,000*
Processor and memory	22	16K words	$25,000	$ 550,000*
VOX processor	17	8	$15,000	$ 255,000
	5	16	18,000	90,000
				$ 345,000*
Combiner	18	9	$ 1,000	$ 18,000
	4	17	2,000	8,000
				26,000*
Splitter	18	9	$ 1,000	$ 18,000
	4	17	2,000	8,000
				$ 26,000*
Reference frequency generator	22		$10,000	$ 220,000*
Total				$2,244,000
VOX option				$ 345,000

*Denotes subtotal.

Table C-45. GMF, DAMA-FDMA System Sizing Chart.

*TERMINAL NUMBER	TOTAL CHANNELS	VOX PROCESSOR		DA PROCESSOR (thousands of words)	IF TRANSLATOR		16-kb/s MODEM	SPLITTER COMBINER		REFERENCE FREQUENCY GENERATOR
		Qty	Size		Tx	Rx		Qty	Size	
1	10	1	16	16	10	10	10	1	17	1
2	11	1	16	16	11	11	11	1	17	1
3	21	1	24	16	21	21	21	1	25	1
4	27	1	32	16	27	27	27	1	33	1
5	28	1	32	16	28	28	28	1	33	1
6	28	1	32	16	28	28	28	1	33	1
7	30	1	32	16	30	30	30	1	33	1
8	32	1	32	16	32	32	32	1	33	1
9	33	1	40	16	33	33	33	1	33	1
10	33	1	40	16	33	33	33	1	33	1
11	34	1	40	16	34	34	34	1	41	1
12	35	1	40	16	35	35	35	1	41	1
13	36	1	40	16	36	36	36	1	41	1
14	40	1	40	16	40	40	40	1	41	1
15	41	1	48	16	41	41	41	1	41	1
16	45	1	48	16	45	45	45	1	49	1
17	56	1	56	16	56	56	56	1	57	1
18	74	1	80	32	74	74	74	1	81	1
19	87	1	88	32	87	87	87	1	89	1
20	135	1	136	DOS	135	135	135	1	137	1

*The total system includes three of each of these terminals.

Table C-46. Cost for DAMA-FDMA, GMF.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
Tx if translator	836		$ 2,000	$ 1,672,000*
Rx if translator	836		$ 2,000	$ 1,672,000*
16-kb/s modem	836		$ 5,000	$ 4,180,000*
Processor and memory	17	16K words	$25,000	$ 425,000
	2	32K words	57,000	114,000
	1	DOS	81,000	81,000
				$ 620,000
VOX processor	2	16	$18,000	$ 36,000
	1	24	21,000	21,000
	5	32	24,000	120,000
	6	40	27,000	162,000
	2	48	30,000	60,000
	1	56	33,000	33,000
	1	80	42,000	42,000
	1	88	45,000	45,000
	1	136	63,000	63,000
				$ 582,000*
Combiner	2	17	$ 2,000	$ 4,000
	1	25	3,000	3,000
	7	33	4,000	28,000
	5	41	5,000	25,000
	1	49	6,000	6,000
	1	57	7,000	7,000
	1	81	10,000	10,000
	1	89	11,000	11,000
	1	137	17,000	17,000
				$ 111,000*
Splitter	2	17	$ 2,000	$ 4,000
	1	25	3,000	3,000
	7	33	4,000	28,000
	5	41	5,000	25,000
	1	49	6,000	6,000
	1	57	7,000	7,000
	1	81	10,000	10,000
	1	89	11,000	11,000
	1	137	17,000	17,000
				$ 111,000*

Table C-46. Cost for DAMA-FDMA, GMF (Cont).

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
Reference frequency generator	20		*$10,000*	$ *200,000**
Total				$ 8,566,000
				x 3
Total system cost				$25,698,000
VOX option				$ 1,746,000
*Denotes subtotal.				

Table C-47. DCS, DAMA-FDMA System Sizing Chart.

TERMINAL NUMBER	TOTAL CHANNELS	VOX PROCESSOR		DA PROCESSOR (thousands of words)	IF TRANSLATOR		16-kb/s MODEM	SPLITTER COMBINER		REFERENCE FREQUENCY GENERATOR
		Qty	Size		Tx	Rx		Qty	Size	
1	13	1	16	16	13	13	13	1	17	1
2	13	1	16	16	13	13	13	1	17	1
3	15	1	16	16	15	15	15	1	17	1
4	25	1	32	16	25	25	25	1	25	1
5	25	1	32	16	25	25	25	1	25	1
6	25	1	32	16	25	25	25	1	25	1
7	25	1	32	16	25	25	25	1	25	1
8	37	1	40	16	37	37	37	1	41	1
9	41	1	48	16	41	41	41	1	41	1
10	41	1	48	16	41	41	41	1	41	1
11	45	1	48	16	45	45	45	1	49	1
12	57	1	64	16	57	57	57	1	57	1
13	57	1	64	16	57	57	57	1	57	1
14	57	1	64	16	57	57	57	1	57	1
15	57	1	64	16	57	57	57	1	57	1
16	71	1	72	32	71	71	71	1	73	1
17	71	1	72	32	71	71	71	1	73	1
18	103	1	104	32	103	103	103	1	105	1
19	108	1	112	32	108	108	108	1	113	1
20	157	1	160	DOS	157	157	157	1	161	1
21	213	1	216	DOS	213	213	213	1	217	1

Table C-48. Cost for DAMA-FDMA, DCS.

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
Tx if translator	1256		$ 2,000	$ 2,512,000*
Rx if translator	1256		$ 2,000	$ 2,512,000*
16-kb/s modem	1256		$ 5,000	$ 6,280,000*
Processor and memory	15	16K words	$25,000	$ 375,000
	4	32K words	57,000	228,000
	2	DOS	81,000	162,000
				$ 765,000*
VOX processor	3	16	$18,000	$ 54,000
	4	32	24,000	96,000
	1	40	27,000	27,000
	3	48	30,000	90,000
	4	65	36,000	144,000
	2	72	39,000	78,000
	1	104	51,000	51,000
	1	112	54,000	54,000
	1	160	72,000	72,000
	1	216	93,000	93,000
				$ 759,000*
Combiner	3	17	$ 2,000	$ 6,000
	4	25	3,000	12,000
	3	41	5,000	15,000
	1	49	6,000	6,000
	4	57	7,000	28,000
	2	73	9,000	18,000
	1	105	13,000	13,000
	1	113	14,000	14,000
	1	161	20,000	20,000
	1	217	27,000	27,000
				$ 159,000*
Splitter	3	17	$ 2,000	$ 6,000
	4	25	3,000	12,000
	3	41	5,000	15,000
	1	49	6,000	6,000
	4	57	7,000	28,000
	2	73	9,000	18,000
	1	105	13,000	13,000
	1	113	14,000	14,000
	1	161	20,000	20,000
	1	217	27,000	27,000
				$ 159,000*

Table C-48. Cost for DAMA-FDMA, DCS (Cont).

UNIT TYPE	QUANTITY		UNIT COST	TOTAL COST
	Qty	Size		
Reference frequency generator	21		$10,000	$ 210,000*
Total				$12,597,000
VOX option				$ 759,000
*Denotes subtotal.				

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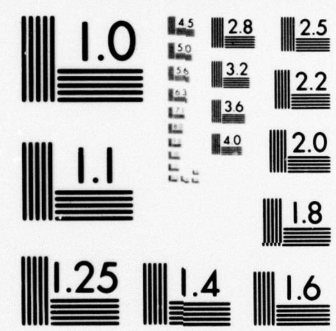

MICROCOPY RESOLUTION TEST CHART

C.7 COST SUMMARY

Please refer to table C-49 for the comparison of system costs as taken from the previous cost sheets.

C.8 SYSTEM MTBF

The system MTBF is calculated for a minimum system configuration. An 8-channel system was chosen as a basis for comparison of the various techniques. Tables C-50 through C-58 illustrate the MTBF calculation for each configuration. Table C-59 summarizes the system MTBF calculations.

Table C-49. System Cost Comparison.

SYSTEM	FLTOPS	GMF	DCS
BDA TDM-TDMA	$1,324,000	$ 4,416,000	$ 1,665,000
with TASI	1,445,000	5,812,500	2,121,500
BDA TDM-FDMA	4,587,000	40,899,000	16,003,000
with TASI	4,231,000	36,803,000	14,098,000
BDA FDM-FDMA	2,055,000	23,694,000	11,869,000
with TASI	1,999,000	16,171,500	7,459,500
DAMA-TDMA	1,325,000	4,422,000	1,675,500
DAMA-FDMA	2,244,000	25,698,000	12,597,000
with VOX option	2,589,000	27,444,000	13,356,000

Table C-50. BDA TDM-TDMA, MTBF Calculation.

UNIT	MTBF (hours)
DA processor	260
TDM unit	4,000
Burst modem	6,800
Baseband buffer unit	5,000
System MTBF	225.1

Table C-51. BDA TDM-TDMA With TASI, MTBF Calculation.

UNIT	MTBF (hours)
TASI processor	1,000
DA processor	260
TDM unit	4,000
Burst modem	6,800
Baseband buffer unit	5,000
System MTBF	183.7

Table C-52. BDA TDM-FDMA, MTBF Calculation.

UNIT	MTBF (hours)
DA processor	260
TDM unit	4,000
(8) digital modem	6,800 (8)
System MTBF	189.7

Table C-53. BDA TDM-FDMA With TASI, MTBF Calculation.

UNIT	MTBF (hours)
TASI processor	1,000
DA processor	260
TDM unit	4,000
(8) digital modem	6,800 (8)
System MTBF	159.4

Table C-54. BDA FDM-FDMA, MTBF Calculation.

UNIT	MTBF (hours)
Splitter	50,000
DA processor	260
Reference frequency generator	4,000
Combiner	50,000
(8) receive if translator	25,000 (8)
(8) 16 kb/s modem	7,300 (8)
(8) transmit if translator	25,000 (8)
System MTBF	170.3

Table C-55. BDA FDM-FDMA With TASI, MTBF Calculation.

UNIT	MTBF (hours)
TASI processor	1,000
Splitter	50,000
DA processor	260
Reference frequency generator	4,000
Combiner	50,000
(8) receive if translator	25,000 (8)
(8) 16 kb/s modem	7,300 (8)
(8) transmit if translator	25,000 (8)
System MTBF	145.5

Table C-56. DAMA-TDMA, MTBF Calculation.

UNIT	MTBF (hours)
DA processor	260
Baseband buffer unit	5,000
TDM unit	4,000
Burst modem	6,800
System MTBF	225.1

Table C-57. DAMA-FDMA, MTBF Calculation.

UNIT	MTBF (hours)
DA processor	260
(8) Rx if translator	25,000 (8)
(8) Tx if translator	25,000 (8)
(8) 16 kb/s modem	7,300 (8)
Combiner	50,000
Reference frequency generator	4,000
Splitter	50,000
System MTBF	170.3

Table C-58. DAMA-FDMA With VOX, MTBF Calculation.

UNIT	MTBF (hours)
VOX processor	1,000
DA processor	260
(8) Rx if translator	25,000 (8)
(8) Tx if translator	25,000 (8)
(8) 16 kb/s modem	7,300 (8)
Combiner	50,000
Reference frequency generator	4,000
Splitter	50,000
System MTBF	145.6

Table C-59. MTBF Summary.

SYSTEM	MTBF (hours)
BDA TDM-TDMA	225.1
with TASI	183.7
BDA TDM-FDMA	189.7
with TASI	159.4
BDA FDM-FDMA	170.3
with TASI	145.5
DAMA-TDMA	225.1
DAMA-FDMA	170.3
with VOX	145.6